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EXPERIMENTAL

ELECTRICAL ENGINEERING

AND

MANUAL FOR ELECTRICAL TESTING

FOR ENGINEERS AND FOR STUDENTS IN
ENGINEERING LABORATORIES

BY
V. KARAPETOFF

VOL. I.

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PREFACE TO THE FIRST EDITION.

In preparing this book the author has aimed to produce a laboratory manual suitable for general electrical-engineering work such as is covered during the Junior and Senior years in most American colleges of engineering. The experiments described cover the principal types of electrical machinery and auxiliary devices, as well as the most important commercial applications of electricity. Some knowledge of physics is assumed on the part of the student, and at least some elementary practice in a physical laboratory; but, for completeness of treatment several experiments are described recalling to the student's mind the fundamental physical laws of electricity and magnetism in their simpler practical aspects.

The arrangement of the book is such as to make each chapter as far as possible independent; in this way the laboratory experiments may be performed in almost any desired order, to suit the equipment at hand and the schedule of the class-room exercises. For the same reason cross-references have been avoided as much as possible. Each chapter covers one particular class of machinery or electrical relations; the experiments of the chapter are described in an ascending scale of difficulty or importance. For instance, the chapters on direct-current machines and on alternators are subdivided into (1) operating features, (2) commercial tests, and (3) a more advanced study of the magnetic circuit and armature windings. For easy reference, the experiments in each chapter bear the name of the chapter. Thus, the experiments in the third chapter are numbered: 3-A, 3-B, 3-C, etc.

The laboratory schedule can be arranged, if desired, so as to cover all the experiments of a particular chapter in succession; but the author greatly prefers the so-called *concentric* disposition of the course. In accordance with this method the Junior-year course is made up of elementary experiments selected from nearly all the chapters of the book; the student being thus introduced to the whole domain of electrical engineering. Then during the first term of his Senior year he performs more advanced experiments relating to the *same* subjects. Finally,

during the second term he is given still more special tests (again on the same subjects) requiring a more mature understanding of the theory.*

The concentric method has marked advantages over the usual method with which the student is first given a thorough training in one subject, say direct-current machinery, before he is allowed to take up the next subject, for instance, alternating-current machinery. The principal advantage is that the "concentric" method is more in accordance with human nature; we always desire a bird's-eye view of a subject before we care to go into the details of a particular branch. In this way the course is made more interesting and more correct from a psychological point of view. Another advantage is that the student is brought in contact with the same subject at least three times during the course, and not only is he not allowed to forget it, but he sees it each time from a more advanced standpoint.

There are also some minor advantages of the concentric arrangement. For instance, the student is better prepared for practical work during the summer between his Junior and Senior years if he has handled all classes of machinery in the Junior laboratory; he is prepared to read electrical periodicals; he can be given more delicate apparatus in the Senior laboratory, etc. The laboratory equipment may be utilized much better if various sections of students are allowed to work on entirely different subjects. However, as was mentioned above, the book may be used with any order in which the experiments might be performed in the laboratory.

The plan followed in each chapter is this: first the particular class of machinery is described and the practical needs for certain arrangements and procedures of operation are given; then the object and the method of each particular experiment are described in detail, and instructions given for the manner in which data should be taken. At the end of most experiments the requirements for the reports are stated so that the student will not omit to take all the necessary readings and dimensions while in the laboratory.

It is advisable to have printed data sheets for the more complicated experiments; this will lead the student to take readings neatly and systematically and to record the general information about the apparatus. In some cases diagrams of connections and the necessary precautions to be observed should be posted near the apparatus.

Some teachers may think this is too much guidance, and that no margin for original thinking is left the student. Experience shows,

* See also the author's papers on "The Concentric Method," in the Transactions of the American Institute of Electrical Engineers, 1907, and in the Proceedings of the Society for the Promotion of Engineering Education, 1908.

however, that it is advisable first to acquaint students with good and efficient methods of experimenting; more individual freedom may be given in more advanced stages of the work.

The author wishes to express his appreciation of the assistance rendered to him by the instructors in the Electrical Engineering Laboratory of Cornell University in giving him valuable suggestions from their experience. He also wishes to acknowledge the moral support which he received from Professors R. C. Carpenter, H. J. Ryan, and H. H. Norris in the preparation of this book. To several manufacturers of electrical apparatus he is under obligation for valuable information and electrotypes.

The author is also indebted to his friend Mr. B. C. Dennison, of the Department of Electrical Engineering of Cornell University, for reading the manuscript and proofs. His painstaking care and unselfish interest were of inestimable value in forwarding the publication of the book.

CORNELL UNIVERSITY, ITHACA, N.Y.,
October, 1907.

PREFACE TO THE SECOND EDITION

THE second edition differs from the first mainly in that the book is divided into two volumes. The first volume contains the more elementary experiments and tests of a general character suitable for a beginner. The second volume contains the more advanced and special experiments and tests. The division has been made for two purposes: first, to meet the needs of non-electrical students and engineers, who will probably obtain from the first volume all the information required; second, to make it possible for students in electrical engineering to postpone the purchase of the second volume until it is required. An incidental advantage is that the student has to carry a much smaller book to the laboratory.

No general revision of the book has been attempted, but a considerable number of corrections have been made, partly indicated by critics, partly from the author's own experience. All the vector diagrams have been made uniform, with counter-clockwise rotation. The vectors of currents, voltages, and fluxes are distinguished by different arrowheads. Most of the half-tone illustrations have been replaced by clearer line-cuts, and provided with explanations. For convenient reference, an index to both volumes is bound at the end of each volume.

A complete list of experiments will be found in each volume, after the table of contents. Teachers will find this list convenient in making up their schedules of laboratory experiments.

The book differs somewhat from other laboratory manuals in that considerable space is devoted to descriptions of the performance of various types of electrical machinery. The descriptive matter is presented in such a manner as to assist the student in understanding the phenomena in the machine under test. In this way he is enabled to perform the actual manual labor connected with the test in the most effective way, and with an added interest in his work. It is practically impossible to connect the laboratory instruction with the theoretical courses in electrical engineering in such a way as to obviate the necessity for descriptive matter in a laboratory manual. In fact, it is convenient to subdivide and to coördinate the courses, so as to treat some topics in the laboratory course, others in the theoretical courses. A laboratory "topic" includes (1) a preliminary report, (2) a recitation preceding or following the experiment, (3) the experiment itself, and (4) a thorough report on the same. In this way the topic is covered both theoretically and experimentally and there is no need for taking it up again in another course. The book is written, therefore, with the view not only of giving explicit instruction for the laboratory work proper, but also as a text for laboratory recitations, and for an intelligent interpretation of the experimental results in the report. The explanations given do not relieve the student from the task of verifying the theory, but do relieve him from searching for subjects not readily accessible.

CORNELL UNIVERSITY, ITHACA, N.Y.,
September, 1910.

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EXPERIMENTAL ELECTRICAL ENGINEERING

CHAPTER I.

MEASUREMENT OF RESISTANCES.

1. Experience shows that electrical conductors offer a certain opposition to the passage of an electric current. It is necessary, therefore, to apply a difference of potential, or an electromotive force, at the ends of the conductor to produce a flow of current in it. This is analogous to a difference of pressure necessary at the ends of a pipe in order that water may flow through it. It is also found that the electrical pressure E to be applied at the ends of a conductor is proportional to the current I desired to be produced in the conductor. In other words,

$$E = RI$$

where R is a coefficient of proportionality, called the *resistance* of the conductor. This experimentally determined relation between electromotive force and current is called Ohm's law. The greater the resistance R, the higher must be the electromotive force E to produce a certain current I. In this respect electrical resistance R is analogous to friction between the walls of a pipe and water flowing through it; the more this friction the higher the pressure required to produce the same flow of water in the pipe.

The resistance of a conductor is its most important electrical feature, and various methods have been devised for accurately measuring and comparing resistances. The practical unit of resistance is called *the ohm*. According to the definition of this unit established by an international agreement, it is represented by the resistance of a column of mercury of a definite length and cross-section and at a definite temperature. The reasons for selecting this unit, and the relation of the ohm to the absolute or c.g.s. (centimeter-gram-second) system, possess little interest for practical engineers. For them it is an arbitrary unit of which the prototype is carefully preserved by the respective governments, and to which prototype secondary standards in practical use are compared.

Two methods for measuring resistances are most often used in practice:

(a) Drop-of-potential method;

(b) Wheatstone bridge.

The first method is based directly on Ohm's law given above; the second is a zero, or balance, method, the unknown resistance being compared to a standard. These, and some other methods, are described below and illustrated in application to some important practical problems.

DROP-OF-POTENTIAL METHOD.

2. The resistance of a conductor is determined by this method as the ratio of a voltage at the terminals of the conductor to the current produced by this voltage. The necessary connections are shown in Fig. 1. X is the unknown resistance which is connected in series with a source of current, such as the battery Ba. The current strength is adjusted by the rheostat K, and is measured on the ammeter A. A voltmeter is connected across the terminals of the resistance X.

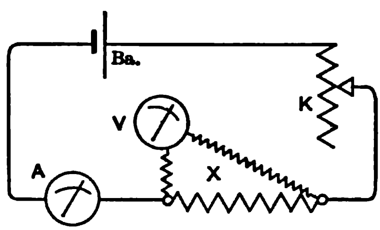

FIG. 1. Measurement of resistance by the drop-of-potential method.

If E is the voltmeter reading in volts, and a current of I amperes is read simultaneously on the ammeter, the resistance of the conductor $X = E \div I$ (in ohms). This is according to Ohm's law mentioned in § 1.

Usually several readings are taken with different values of the current, and an average calculated of the corresponding values of R. It is important not to use too large a current which might appreciably heat the conductor. Experience shows that the resistance of most conductors depends on their temperature; in making measurements it is therefore necessary to note to what temperature they refer.

As a further precaution, the current flowing through the voltmeter must be negligible as compared to that flowing through the resistance X; otherwise a correction may be necessary for the ammeter reading. Suppose, for instance, that the voltmeter shows 100 volts, and the ammeter reading be 0.5 ampere. Let the resistance of the voltmeter itself be 10,000 ohms. At a pressure of 100 volts, the current through the voltmeter is 100/10,000 = 0.01 ampere. Therefore, the true current through X is 0.50 − 0.01 = 0.49 ampere, and the unknown resistance $X = 100 \div 0.49 = 204$ ohms.

Employing this method for very accurate measurements, a potentiometer is used (§ 63), or a static voltmeter (§ 43) instead of an ordinary voltmeter; with either of these no current is shunted around X, and no correction is necessary.

A modification of the drop-of-potential method is shown in Fig. 2; here a standard resistance R is used in place of the ammeter, and the voltage drop is taken in succession, first across R, then across X. Let the readings be E_R and E_x. If the current I has not changed during the measurement, we have,

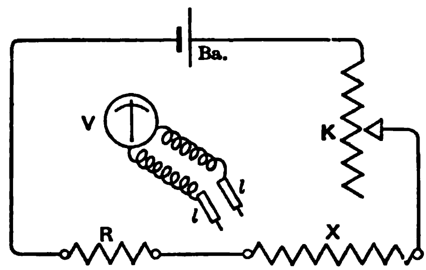

FIG. 2. Comparison of resistances, using a voltmeter.

$$I = \frac{E_R}{R} = \frac{E_x}{X},$$

or

$$X = R\frac{E_x}{E_R}.$$

The voltmeter is conveniently transferred from one resistance to the other by using flexible leads ll. The advantage of this method is that only one instrument, instead of two, needs to be calibrated, and even for this one instrument it is not necessary to know the actual values of divisions on its scale, since only the ratio of the readings enters into the result. Where extremely accurate results are required R and X are compared by means of a potentiometer (see § 43).

Experiments and practical tests to be described later illustrate the drop-of-potential method.

3. Influence of Length, Cross-Section and Material of a Conductor on its Resistance. — It is found that the resistance of a conductor (a) increases in proportion to its length, and (b) varies in an inverse ratio with its cross-section. Hence, the resistance may be expressed by the formula

$$R = k\frac{l}{q} \quad \dots \dots \dots \dots \quad (1)$$

where l is the length of a conductor, q is its cross-section, and k a physical constant which characterizes the material of the conductor. This again is analogous to the flow of water through a pipe: the longer the pipe, the greater is its frictional resistance; the larger its cross-section, the easier it is to force through it a certain quantity of water per minute.

The constant k is called the *specific resistance* of the material of a conductor. Its physical meaning is: resistance of a conductor of unit length and of unit cross-section. The length is usually measured in feet, the cross-section in circular mils. A circular mil is the area of a circle having a diameter of 1 mil = 0.001 inch.

For copper, k = about 10 ohms at ordinary room temperature, which means that the resistance of a piece of copper wire 1 ft. long and of a cross-section of 1 circular mil is about 10 ohms. The electrical resistance of most metals increases appreciably with temperature, therefore, in stating a resistance, it is necessary to mention to what temperature it refers.

4. EXPERIMENT 1-A. — Determining Influence of Length, Cross-Section and Material of a Conductor on its Resistance. — The purpose of the experiment is to verify the relations stated in the preceding paragraph and to determine the specific resistance k for a few metals used in practice. The connections are shown in Fig. 1; or, if preferred, the method shown in Fig. 2 may be used. Insert the wire to be tested, in place of X, and adjust the current by the rheostat K. Read the current on the ammeter, and the voltage drop across a certain length of the wire. Use knife-edge contacts at the end of the voltmeter leads, in order to insure a good contact and to have a definite length of wire. Reduce the current in steps and read the corresponding voltages.

Repeat the same experiment on wires of (a) different length, (b) different cross-section, (c) different materials. The metals of chief importance in electrical engineering are: copper, aluminum, iron, German silver, and manganin. In each case vary but one factor entering into the formula (1); keep the other factors constant. With each sample of wire take several readings of volts and amperes in order to eliminate possible errors and to obtain more accurate results. Do not use large currents, which might appreciably heat the conductors under test; unless you have a means for ascertaining the temperature of the conductor. When accurate results are required, conductors are immersed in an oil-bath maintained at a definite temperature. Before leaving the laboratory measure the lengths and the cross-sections of the samples tested.

Report. (1) Figure out the resistances of the samples tested; this being done by dividing volts by the corresponding amperes. It is best to average the readings for each sample. A short way to do this is as follows: plot the observed volts to amperes as abscissæ on a sheet of cross-section paper, and draw a straight line passing through the origin

and the points thus obtained. The average resistance is then calculated from any point on this line.

(2) Show from the results of the experiment that resistances are directly proportional to the length of a conductor and inversely proportional to its cross-section.

(3) Calculate the specific resistance k for the materials tested, using the foot and circular mil as the units.

5. Influence of Temperature on the Resistance of Conductors. — The electrical resistance of metals increases with their temperature; within practical limits the increase in resistance is usually assumed as proportional to the temperature rise. For copper the resistance increases 0.42 per cent for each degree centigrade, *the resistance at* 0°C. *being assumed as* 100 *per cent*. Thus, if the resistance of a copper conductor at 15 degrees C. (R_{15}) is 5 ohms, then, since

$$R_{15} = R_0\,(1 + .0042 \times 15),$$

the resistance at 25° C. is

$$R_{25} = R_0\,(1 + .0042 \times 25) = R_{15}\left(\frac{1 + .0042 \times 25}{1 + .0042 \times 15}\right).$$

Substituting the value of R_{15}, we find $R_{25} = 5.197$ ohms. A constant, such as 0.0042, is called the temperature coefficient of a conductor; it varies within wide limits with different substances.

Liquids have a negative temperature coefficient; their resistance decreasing with the increase in temperature.

In solving various practical problems it is of importance to know the temperature coefficient or per cent increase of resistance with temperature for various substances. Thus, for instance:

(1) Resistances used as standards must be made of materials having a negligible temperature coefficient.

(2) Some protective resistances (for instance, those used in Nernst lamps) are made of a material whose resistance increases rapidly with temperature. This protects the apparatus against excessive currents.

(3) Knowing the temperature coefficient of a material, temperature rise in electrical windings may be measured more accurately than with an ordinary thermometer; also in places where it would be impossible to reach with a thermometer.

Iron is interesting in that its resistance increases rather slowly at ordinary temperatures, and very rapidly when it is just beginning to glow dull red. This is the reason for using iron for protective resistances in Nernst lamps.

Resistance of carbon decreases with increasing temperature; therefore carbon is spoken of as having a negative temperature coefficient. For

this reason, the current in an incandescent lamp increases more rapidly than the terminal voltage. This is an undesirable feature, since it makes the lamp particularly sensitive to voltage fluctuations.

6. EXPERIMENT 1-B. —Determination of Temperature Coefficient of Metal Conductors. —The experiment is performed in a way similar to Experiment 1-A; the materials tested must be placed in an oil-bath maintained at a definite temperature. The bath is heated gradually, and readings of volts and amperes are taken as in Fig. 1 every few minutes. The corresponding temperatures are read on a thermometer placed in the oil. Perform this experiment with materials such as iron or copper which have an appreciable temperature coefficient, and with manganin and German silver which have a negligible temperature coefficient.

Observe the rapid increase in resistance of an iron wire as it becomes dull red. The wire may be heated by the same current by which the resistance is measured. No oil-bath is used with this experiment, and only qualitative results are expected.

Demonstrate that the resistance of carbon decreases with an increase in temperature. This can be easily shown on the filament of an ordinary incandescent lamp. Gradually raise the voltage at the terminals of the lamp and read the corresponding values of the current. Refer the readings to the states of incandescence, thus: the lamp just begins to glow, dull red, red, bright red, yellow, white, brilliant white.

Report. (1) Calculate the values of the temperature coefficient for the materials tested.

(2) Give the results of the test on the iron wire at dull incandescence.

(3) Plot the resistances of the incandescent lamp to terminal volts as abscissæ; mark on the curve the stages of incandescence.

7. EXPERIMENT 1-C. —Determination of Temperature Rise in Windings by the Increase in Resistance. —This problem is the inverse of that in the preceding experiment. The temperature coefficient is now assumed to be known, and the temperature rise of a coil of wire is calculated from the observed increase in its resistance.

Suppose, for instance, the resistance of a coil of copper wire to be 4.573 ohms at 15 degrees C., while at some unknown temperature it was found to be 5.468 ohms. For copper, resistance increases 0.42 per cent for each degree centigrade; therefore, the resistance of the coil at 0°C. is

$$\frac{4.573}{1 + .0042 \times 15} = 4.302 \text{ ohms.}$$

The per cent increase of resistance to the unknown temperature is

$$\frac{5.468 - 4.302}{4.302} = 27.1 \text{ per cent.}$$

Therefore, the unknown temperature is

$$\frac{27.1}{0.42} = 64.5° \text{ C.}$$

This is the method regularly used for the determination of temperature rise in windings of electrical machinery. A measurement by thermometers is not sufficient, because the temperature of the outside layers may be considerably below that in the center of the coil (Fig. 3). An excessive temperature rise inside the coil deteriorates the insulation and finally causes a short-circuit.

Temperature rise in a coil depends essentially upon the conditions of cooling. In some cases, as for instance in transformers, coils are cooled artificially by immersing them in oil or by subjecting them to a draft of air, (oil-cooled and air-cooled transformers). To illustrate this there is provided the following experiment.

Take three identical coils, connect them in series and investigate temperature rise under different conditions of cooling: Place one coil in a space protected from draft; put another coil in an oil-bath; subject the third coil to an artificial draft — that, for instance, produced by an electric fan. Adjust the current so that the coil without artificial cooling would be heated up to its safe limit in a reasonable amount of time — about an hour. Read the current through the coils and the

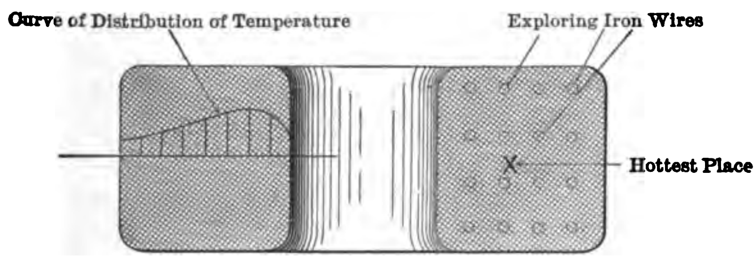

FIG. 3. Cross-section of a coil, showing exploring wires and distribution of temperature.

voltage drop across each coil every few minutes. Note the temperature on the surface of the coils with ordinary thermometers, as a check on the resistance measurements.

Such a test gives only an average temperature rise throughout the coil, but not the maximum temperature of the central layers (Fig. 3). The distribution of temperature within a coil may be investigated by

placing exploring wires in various places, as shown by small circles. The temperature rise is determined by the increase in the resistance of the exploring wires. Iron is the most suitable material for such wires, because it has a considerable temperature coefficient. The terminals of each exploring coil are brought out separately; the resistance is measured from time to time while the coil under test is being heated by a current. It is not safe to take the value of temperature coefficient of iron given in standard tables; this coefficient must be determined on a sample taken from the wire used for the exploring coils.

Instead of measuring temperature rise by the increase in resistance, exploring wires may contain thermal junctions previously calibrated for temperature rise.

Report. Plot curves of temperature rise for the three coils tested under different conditions of cooling. Give the distribution of temperature inside of the coil, as shown in Fig. 3.

8. Resistances in Series and in Parallel. — Resistances are connected in electrical circuits in various combinations; it is sometimes required to determine the value of a resistance which would produce the

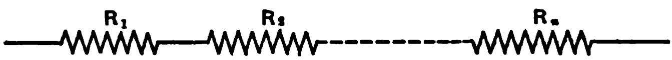

FIG. 4. Resistances in series.

same electrical effect as two or more given resistances. Such a resistance is called the *equivalent* or the *resultant* resistance. A few simple cases are here considered.

(1) *Resistances in Series.* From the conception of electrical resistance, it follows that two resistances R_1 and R_2 (Fig. 4) connected in series are equivalent to a resistance $(R_1 + R_2)$. The same is true for any number of resistances in series, so that

$$R_{\text{equiv.}} = \sum_1^n R \qquad (2)$$

(2) *Resistances in Parallel* (Fig. 5). The equivalent resistance in this case is less than either of the component resistances, because the addition of each resistance means a new path for the current. Let the common voltage across the resistances be e; the currents i_1, i_2, etc. We then have

$$i_1 = \frac{e}{R_1};\ i_2 = \frac{e}{R_2};\ \text{etc.} \qquad (3)$$

The equivalent resistance must by definition have such a value that the same total current Σi would flow through it with the same voltage e; hence

$$\sum_1^n i = \frac{e}{R_{\text{equiv.}}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

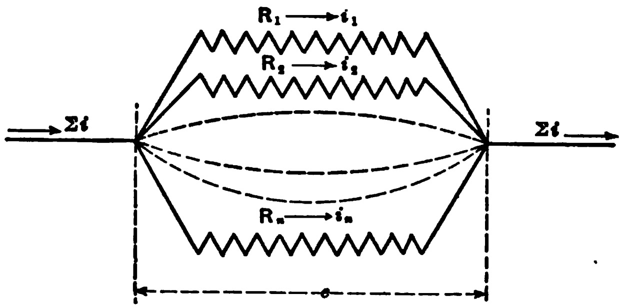

FIG. 5. Resistances in parallel.

Substituting the values of i_1, i_2, etc. from (3) we have

$$\sum_1^n \frac{e}{R} = \frac{e}{R_{\text{equiv.}}};$$

or, dividing both members of the equation by e:

$$\frac{1}{R_{\text{equiv.}}} = \sum_1^n \frac{1}{R} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

This formula gives the value of the equivalent resistance in terms of the component resistances. The reciprocal value of a resistance is sometimes called the *conductance;* the result (5) indicates that the

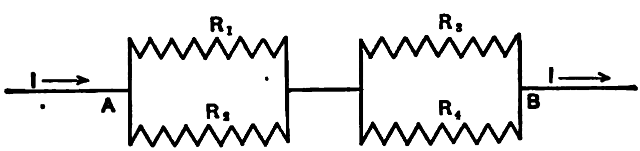

FIG. 6. Combination of resistances in series and in parallel.

equivalent conductance is equal to the sum of conductances of the branches connected in parallel. Denoting the conductances by G, we have

$$G_{\text{equiv.}} = \sum_1^n G \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

which is analogous to the expression (2).

(3) *Series-parallel Resistances.* The problem (illustrated in Fig. 6) is to find a resistance, equivalent to the combination of resistances shown

First find a resistance r' equivalent to the resistance offered by R_1 and R_2, by using formula (5); in the same way find the resistance r'' equivalent to R_3 and R_4. The equivalent resistance of the whole combination is $(r' + r'')$.

A more complicated combination of resistances in series and in parallel is shown in Fig. 7. It corresponds to the practical case of a transmission line $OeO'e'$ with current-consuming devices $R_1, R_2, \ldots R_5$ connected at different places. The problem is to find one single resistance which would give the same total current, with the same supply voltage between O and O'.

The problem is solved in steps: The resistances R_4 and $(2\, r_5 + R_5)$ are connected in parallel between the points d and d'. Their equivalent resistance R_4' according to the formula (5) may be calculated from the expression

$$\frac{1}{R_4'} = \frac{1}{R_4} + \frac{1}{R_5 + 2r_5};$$

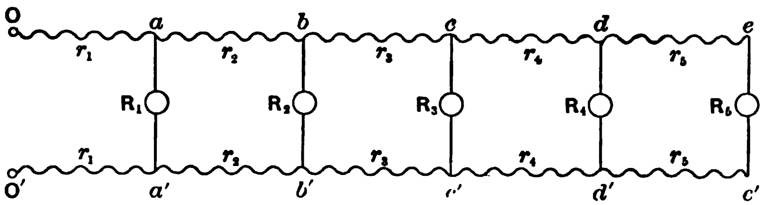

FIG. 7. Current-consuming devices R_1, R_2, etc., connected across a transmission line of appreciable resistance.

In a similar manner we find

$$\frac{1}{R_3'} = \frac{1}{R_3} + \frac{1}{R_4' + 2r_4};$$

$$\frac{1}{R_2'} = \frac{1}{R_2} + \frac{1}{R_3' + 2r_3};$$

$$\frac{1}{R_1'} = \frac{1}{R_1} + \frac{1}{R_2' + 2r_2};$$

and finally

$$R_{\text{equiv.}} = R_1' + 2r_1.$$

The problem is solved by calculating R_4' from the first equation and substituting its value into the second equation; then R_3' is calculated from this equation and its value substituted in the next equation, etc.

9. EXPERIMENT 1-D. —Exercises with Resistances in Series and in Parallel. — Take several resistances of suitable value and measure them separately by the drop-of-potential method. Connect the resistances as shown in Figs. 4 to 7, or in any combinations desired and measure the resultant (equivalent) resistance. See how closely the results check with the formulæ given in the preceding article.

10. EXPERIMENT 1-E. — Measuring Resistance of D. C. Armatures. — A current is passed through the armature in question from an external source, and the voltage at the armature terminals measured with a low-reading voltmeter. The ratio of the voltage to the current gives the resistance of the armature. In performing this measurement it is advisable to hold the voltmeter leads once on the terminals of the machine, and then on the commutator bars. This will make it possible to separate the armature resistance proper from that due to the contact resistance at the brushes, and to the resistance of the brushes themselves.

This contact resistance is different when the machine is at rest, and when it is running. To see the difference, the machine may be run at a low speed with the field circuit open, and the same measurement repeated. It must be remembered, however, that even when the field circuit is open, there is some residual magnetism in the field. This magnetism induces a voltage in the armature and may considerably affect the results. In order to eliminate its influence, the measurements must be repeated with the machine running in the opposite direction at exactly the same speed. The average of the two resistances will give the true resistance of the armature.

In stating the results it is necessary to note to which temperature they refer. The resistance of the armature, and therefore the voltage drop, will be somewhat higher when the machine is hot. In contracts and guarantees is usually stated, that voltage drop must not be above a certain figure, when the temperature of the machine is, say, 50 degrees C. above ordinary room temperature. If the resistance was measured when the machine was cold, and again after a continued run at some load (temperature test), the temperature rise in the armature winding may be calculated from the increase in resistance, as explained in § 7.

SUBSTITUTION METHOD.

11. Theory of the Substitution Method. — With this method a current of a definite value is produced in the circuit containing the *unknown* resistance, and then there is substituted for it a *known* resistance of such a value as to give the same current. It is evident then, that the known resistance is equal to the unknown resistance. The connections are shown in Fig. 8; a circuit is formed through the battery Ba, galvanometer Ga, regulating resistance K and the unknown resistance X. A double-throw switch S is provided, which allows a box R of calibrated resistances to be substituted for X. The switch S is first thrown down, and the current adjusted so as to obtain a certain deflection of the galvanometer. After this the switch is thrown up, and R adjusted until

the galvanometer gives the same deflection; then the resistance of R is equal to X.

In using this method care should be taken, that the battery e.m.f.

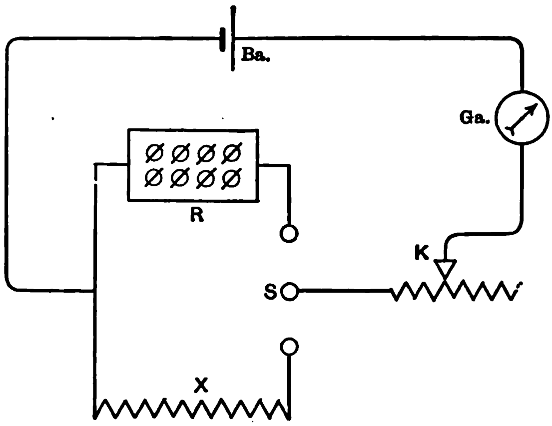

FIG. 8. Substitution method of measuring resistances.

does not change (due to polarization) between the two readings, and also that the resistance K remains constant. Instead of connecting R and X in parallel, they may be connected in series, as shown in Fig. 9, and short-circuited in succession.

The substitution method is sometimes used for measuring high resistances, such as insulation resistances; also for measuring resistance of liquid conductors, as explained in § 12.

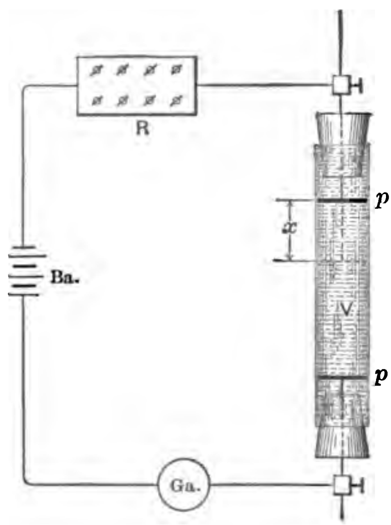

FIG. 9. Measuring resistance of a liquid by the substitution method.

12. Measuring Resistance of Electrolytes by the Substitution Method.—The difficulty in measuring electrical resistance of most liquids is that they are decomposed by current. Gases are deposited on the electrodes, the resistance being thereby increased, and a counter e.m.f. of polarization set up. One way out of this difficulty is to measure the resistance of liquids with alternating currents (see § 21). Another method based on the substitution of resistances is shown in Fig. 9.

The liquid under test is placed in a glass tube V, provided with plugs at both ends, and with the electrodes pp; the upper electrode being adjustable. R is a calibrated resistance box. A certain current is sent through the circuit, until the conditions in the liquid become constant. The deflection of the galvanometer is noted, then the upper electrode p is moved by the amount x, as shown by dotted lines. The current increases, but is brought back to its former value by introducing more resistance R into the circuit. The amount R is evidently equal to the resistance of the column x of the liquid. The effect of the polarization is thus eliminated, as it is present to the same extent with both positions of p.

The resistance of liquids is usually reduced to the resistance of a column 1 cm. high and having a cross-section of 1 sq. cm. This is called the *specific* resistance of the fluid. If the cross-section inside of the glass tube V is Q sq. cm., the specific resistance of the liquid under test is $RQ \div x$. This is evident since resistance is proportional to the length and inversely proportional to the cross-section of a conductor.

13. EXPERIMENT 1-F. —Measuring Resistances by the Substitution Method.—The theory of the method and its application for measuring resistances of solid conductors is given in § 11; the application to liquid conductors is explained in § 12. An experiment should be performed affording practice with the method as illustrated in Figs. 8 and 9.

WHEATSTONE BRIDGE.

14. The combination of conductors known as the Wheatstone bridge (Fig. 10), devised for measuring resistances, has the following features:

(1) The unknown resistance is compared directly to a standard resistance.

(2) No calibrated measuring instrument is required, the adjustment being made by bringing the galvanometer back to zero (null method).

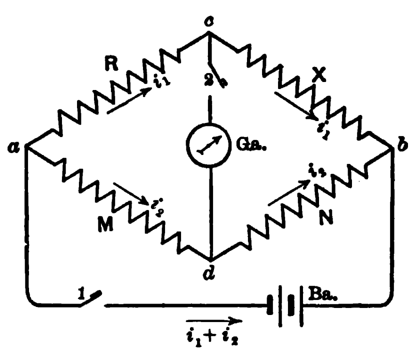

FIG. 10. Diagram of the Wheatstone bridge.

The unknown resistance X and a standard resistance R are connected in series with each other and with the battery Ba. The combination is shunted by two other resistances M and N, the ratio of

which — $N + M$ — is known. The galvanometer is bridged between the two sets of resistances, hence the name "bridge." Contact keys 1 and 2 are provided in the galvanometer and battery circuits.

The battery key 1 is closed first, and a moment later the galvanometer key 2 is closed. If the galvanometer gives a deflection, the "balancing" resistance R and the "ratio" resistances M and N are varied until the galvanometer comes back to zero. Then

$$X : R = N : M \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad (1)$$

Proof: Suppose that the four resistances satisfy the condition that no current flows through the galvanometer; in other words, the difference of potential between the points c and d is zero. From this condition it follows, that the voltage drop in the branch ac is equal to that in the branch ad; or, with the notations in the sketch,

$$Ri_1 = Mi_2.$$

Similarly

$$Xi_1 = Ni_2.$$

Dividing the second equation by the first we obtain the expression (1).

15. Slide-Wire Wheatstone Bridge. — A simple Wheatstone bridge is shown in Fig. 11; the ratio resistances M and N are formed by two

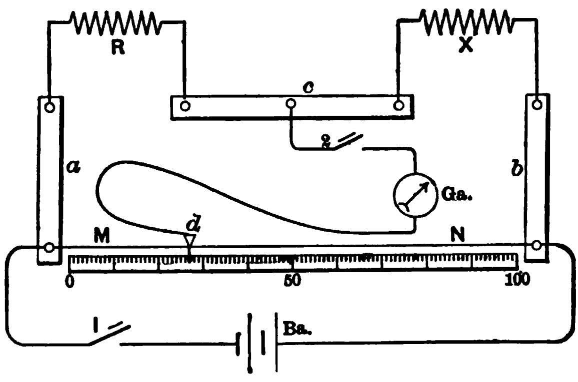

FIG. 11. Diagram of the slide-wire Wheatstone bridge.

parts of a straight wire; the ratio is varied by the sliding contact d. The slide-wire is made of a non-corrodible metal of high specific resistance and of a small temperature coefficient. The brass blocks a, b, c to which R and X are connected have a negligible resistance.

To measure the resistance X, the key 1 is closed first, then the key 2, and the contact d moved along the wire until the galvanometer remains on zero when the key 2 is closed or opened. Suppose the

standard resistance R be = 10 ohm; with the position of the contact shown in the sketch, M = 27 div., N = 73 div.; then, according to formula (1),

$$X = 10\frac{73}{27} = 27.04 \text{ ohm}.$$

The details of the construction of the bridge are shown in Fig. 12;

FIG. 12. Slide-wire Wheatstone bridge, also suitable to be used as a Carey-Foster bridge.

the rider is provided with a vernier so as to read accurately the tenth parts of a division. Extra binding posts and the reversing switch in

FIG. 13. A standard resistance.

the center enable the bridge to be used for the Carey-Foster method, described in § 17.

The balancing resistance R may have various forms; usually it consists of a coil of wire (Fig. 13) wound on a metal spool and protected

by a metal case. The heavy horn terminals are used for suspending the device from mercury cups, in order to minimize the error due to contact resistances. The greatest accuracy of measurement is obtained when X is about equal to R so that the contact d is near the center of the slide-wire.

16. EXPERIMENT 1-G. —Measuring Resistances with a Slide-Wire Bridge. — The theory and the use of the bridge are explained in the two preceding sections. Three kinds of problems may be solved with the bridge:

(a) Checking standard resistances against a primary standard.
(b) Determining values of unknown resistances.
(c) Adjusting resistances to desired values.

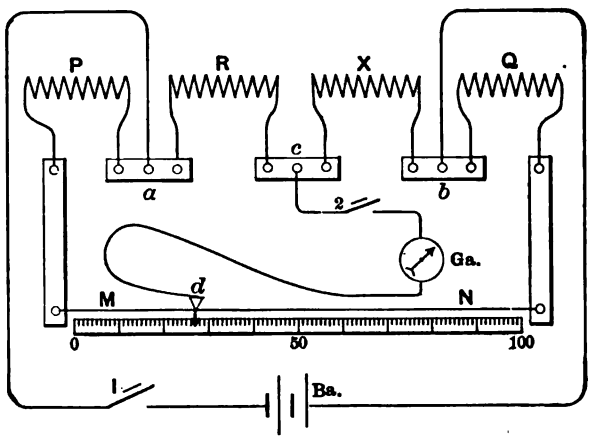

FIG. 14. Carey-Foster bridge.

The student is expected to make himself familiar with the use of the bridge, and to practice in these three problems. No particular accuracy is expected in this exercise, it being only a preparatory one for more advanced work with Wheatstone bridge.

17. Carey-Foster Method for Comparing Resistances. — This is a modification of the ordinary Wheatstone bridge, and is used for an accurate comparison of two resistances nearly equal to each other, as in determinations of per cent error of secondary standards. The connections are shown in Fig. 14; the bridge illustrated in Fig. 12 may be used with this method. P and Q are two resistances to be compared to each other; R and X are two other resistances, of which it is

not necessary to know the numerical values. It is advisable, however, to have R and X not very different from each other, in order to obtain the balance near the center of the slide-wire.

The bridge is balanced as usual; then the positions of P and Q are interchanged by means of the commutator shown in Fig. 12; a new balance is obtained by slightly moving the contact d. The resistance of the slide-wire between the two positions of the contact is equal to the difference of the resistances P and Q.

The reason for this is, that the branches R and X being the same in the two measurements, the total resistance of each of two other branches must also be the same. If P is smaller than Q, the difference must be compensated by the corresponding amount of resistance in the slide-wire.

The method presupposes, that the resistance of the slide-wire per one division of the scale is known. The calibration is made by measuring with the bridge the difference in the resistance of two standards P and Q, which difference has been determined before in some other way. This is best done by taking two equal resistances P and Q, each of perhaps 1 ohm, and to shunt P by a comparatively high resistance, for instance 100 ohms. This reduces the resistance of P to a certain value P'. According to the formula 5 of § 8 we have:

$$\frac{1}{P'} = \frac{1}{1} + \frac{1}{100}; \text{ or } P' = 0.9901 \text{ ohm.}$$

Knowing the difference between Q and P', the slide-wire may be calibrated, at least in the middle portion used for measurements. A balance may be obtained at any desired point of the slide-wire by changing the ratio $X : R$.

18. EXPERIMENT 1-H. —Comparing Resistances by Means of the Carey-Foster Bridge. — The method is explained in § 17, preceding. Special types of Carey-Foster bridge are on the market, with which an accuracy of comparison of over one one-hundredth of a per cent is possible. For ordinary practice with the method the bridge shown in Fig. 12 is sufficient.

(a) Connect four resistances as indicated in Fig. 14 and practice in comparing their values.

(b) Calibrate the slide-wire as explained above.

(c) Determine the limits of accuracy of the method by varying the difference between P and Q, the ratio $R : X$, and the absolute values of the four resistances.

19. Sage Ohmmeter. — A convenient portable Wheatstone bridge of the slide-wire type is shown in Fig. 15; it is known as the Sage ohm-

FIG. 15. Sage ohmmeter

meter, and is intended for all-around practical work, particularly for locating faults in the insulation of wiring installations. The slide-wire is divided into two parts connected electrically; this reduces the length of the case, and at the same time the wire is long enough to give sufficient accuracy. The contact d (Fig. 11) is formed by the stylus shown lying across the top of the instrument. Touching the wire with the stylus closes the galvanometer circuit. The instrument is entirely self-contained ; the galvanometer and a few dry cells are mounted in the case. The telephone receiver shown in front of the instrument may be used, if desired, in place of the galvanometer. Four standard resistances R, usually 1, 10, 100, 1000 ohm, are supplied with the bridge. They are mounted inside of the box, and the leads taken to the four sockets seen on the right side of the middle bar. Any one of them may be used according to the value of the unknown resistance; the desired value is selected by inserting the plug in the corresponding socket.

The scale is calibrated directly in ohms, so that no calculations are necessary. Four sets of figures in different colors are printed on the scale, and the sockets are labeled accordingly. When the plug is in the "blue" socket, blue figures are read on the scale, etc. In this way even an unskilled person can use the bridge with little probability of making a mistake. Uniformly-divided scales are also provided with the instrument, and may be attached in place of the direct-reading scales, if so desired.

An induction coil is shown mounted on the lid of the box; by means of it the bridge may be used with alternating currents. The coil is supplied with current from the battery mounted in the box. The telephone receiver must be used instead of the galvanometer, when using the induction coil. Alternating current is applied where polarization would vitiate results obtained with direct current; as in locating grounds when an electrolytic action between the conductor and the earth is suspected; also for measuring resistance of liquids, as in § 21.

Switches are provided in the instrument for changing to direct or alternating current at will; also for connecting into the circuit either the galvanometer or the telephone receiver. The battery switch is built in the telephone receiver, so that the operator may close the switch with the same hand with which he is holding the receiver to his ear. With the other hand he touches the slide-wire with the stylus, and thus locates the point where the click in the receiver disappears, or is reduced to a minimum.

20. EXPERIMENT 1-I. — Practice with the Sage Ohmmeter. — (a) Inspect the instrument and make clear its connections and operations.

(b) Measure by means of it a box of calibrated resistances, within as wide a range as possible, paying particular attention to the sensitiveness of the instrument at different values of the unknown and the balancing resistances. (1) Perform the measurements first with direct current, using in succession the galvanometer and the telephone receiver; then (2) repeat some of the measurements with the induction coil and the telephone receiver.

(c) Determine the resistance of an electrolyte with direct and with alternating current, and note the difference.

(d) Measure the resistance between a line and the ground (resistance of the fault).

(e) Locate the place of a fault by one of the methods described in §§ 486 and 487. Form your own opinion about the instrument, its advantages and shortcomings, the limits of accuracy, the best range, the relative advantages of using the telephone receiver as vs. the galvanometer, and direct as vs. alternating current.

21. Kohlrausch Bridge. — A disadvantage of a stretched slide-wire, as in Fig. 12, is that it cannot be made long enough for accurate measurements without making the instrument itself too large. Kohlrausch solved this difficulty by winding the slide-wire on an insulating cylinder, as shown in Fig. 16, to the right. The cylinder may be rotated by a handle, contact being made by a roller. The balancing resistances

are placed in the base of the instrument, and may be connected into the circuit by the plugs seen in the sketch.

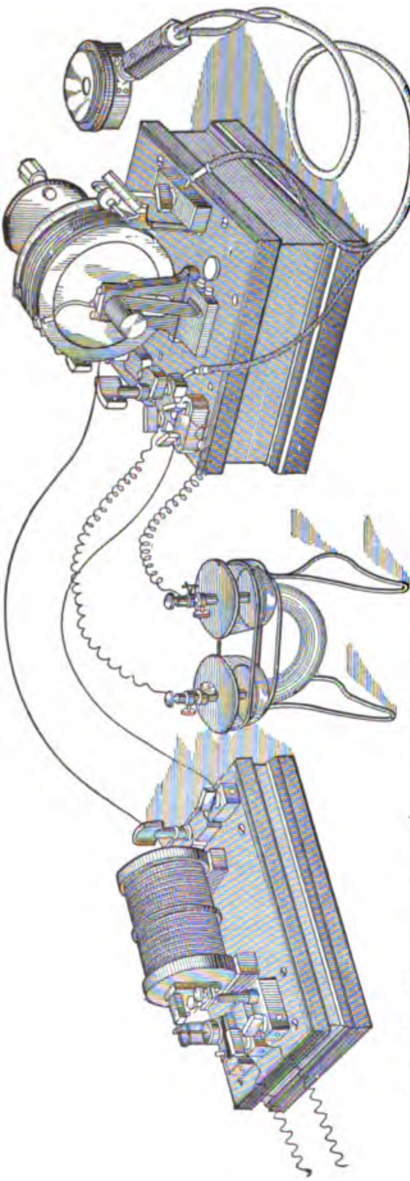

Fig. 16. Measuring resistance of an electrolyte with the Kohlrausch bridge, using alternating current.

The Kohlrausch bridge is particularly well adapted for measuring resistances of liquid conductors with alternating currents (see § 12). An induction coil for producing alternating currents is shown to the left; a telephone receiver is substituted for the galvanometer.

The liquid under test is put into the U-shaped vessel shown between the bridge and the induction coil, this vessel being provided with platinum electrodes on both ends. The form of the vessel is too complicated to allow the specific resistance of the liquid to be deduced as in § 12. This, however, is no serious objection; the constant of the vessel may be determined once for all by measuring in it the resistance of a standard fluid, whose specific resistance is known.

For instance, it is known that the specific resistance of a 25 per cent solution of zinc sulphate is 21.4 ohms per cu. cm. at 18 degrees C. If the resistance of such a solution, as measured in the Kohlrausch vessel to be calibrated, be 152 ohms, then the constant of the vessel is $21.4 \div 152 = 0.141$. The resistance of all other liquids measured in this vessel must be multiplied by this coefficient to get their specific resistances. The Kohlrausch bridge is more convenient for a quick and

accurate determination of resistances of electrolytes than the substitution method described in § 12.

22. EXPERIMENT 1-J. —Measurement of Resistances with Kohlrausch Bridge. — See preceding paragraph.

23. Testing Rail Bonds. — On most electric roads the current for operating cars returns to the station through the track rails; this saves one conductor. In order to make possible the use of the rails for this purpose they must be " bonded " together, or connected by more or less flexible copper conductors as shown in Fig. 17. Rail bonds must be periodically inspected, as they get loose or broken, causing an excessive resistance between the rails. Poor bonding brings with it an

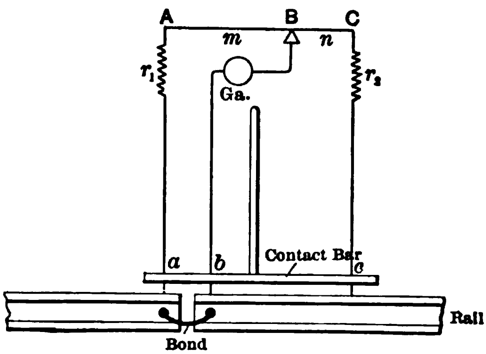

FIG. 17. Diagram of the Roller bond tester,

excessive drop of voltage and loss of power, electrolytic corrosion of gas and water pipes in the vicinity, telephone troubles, etc.

If rail bonds could be tested while the road is not in operation, the simplest method would be to send a current from the station and to measure the drop across each bond with a low-reading voltmeter. Usually, however, testing must be done with cars running on the same line, so that the current in the rails is widely fluctuating. In order to utilize this current special devices are used as described below. The resistance of the bond is expressed in feet of a solid rail; thus a resistance of 2 feet means that the voltage drop caused by the bond contacts is the same as would be caused by two additional feet of solid rail. Convenient methods of testing bonds are as follows:

(a) If no special bond tester is available, *two ordinary milli-voltmeters* may be used, one connected between a and b (Fig. 17), another between b and c. The milli-voltmeters are read simultaneously, so that the fluctuations in the rail current do not affect the ratio of the

readings. This ratio is evidently equal to the ratio of the resistances of the bond *a-b*, and the rail *b-c*. It is advisable to have some protective resistance in series with the milli-voltmeter connected across the bond. The voltage drop across a loose or broken bond may be many times in excess of the range of the instrument. The protective resistance may be short-circuited with a push button. Good contacts with the rail may be obtained either by chisel-ended spikes struck into the rail faces or by using short sections of hack-saw blades.

(b) A convenient device for testing rail bonds — the so-called *Roller bond tester* — is shown in Fig. 18, while a diagrammatic view of its connections is represented in Fig. 17. It operates on the principle of a slide-wire Wheatstone bridge. The unknown resistance *a-b* of the bond is compared to a definite length *b-c* of the solid rail by means of the slide-wire *A-C* and the galvanometer connected between *b* and *B*. The slider *B* is moved back and forth until the galvanometer shows zero. Then the ratio of the resistance of the bond to that of the rail is equal to the ratio $(r_1 + m) \div (r_2 + n)$. It is not necessary to calculate this ratio every time; the scale of the instrument (Fig. 18) gives the resistance directly in feet of solid rail.

FIG. 18. The Roller bond tester.

The resistances r_1 and r_2 act as an extension of the slide-wire, making the useful part of it longer and therefore more accurate. Without these resistances, the short slide-wire would contain all the values from zero to infinity. Fluctuating currents in the rail do not affect the balance, because fluctuations occur in all the branches of the bridge simultaneously.

One observer is sufficient with this instrument; he holds the contact bar by the upright in one hand, and operates the knob of the slider with the other hand. The instrument itself is suspended from his shoulders. The large scale indicates the resistance, the small scale is for galvanometer deflections. In many cases, it is sufficient to know that the resistance of the bond is not beyond a certain limit; then the pointer of the slider is simply set at this limit. On all bonds having resistance below this limit the galvanometer deflects one way, on defec-

tive bonds it shows the other way. This makes the instrument very convenient for rapid testing, even with an unskilled observer.

(c) Another popular *bond tester* is that designed by *Conant.* In it the contact *c* (Fig. 17) is separate from the two other contacts, and the operator's assistant moves it along the rail, until a balance is obtained. A telephone receiver is used instead of a galvanometer, and the current is periodically interrupted by a wheel driven by a clock-work. The balance is reached when the click in the telephone disappears; the equivalent length of the rail is then measured directly with a foot rule.

24. EXPERIMENT 1-K. — Testing Rail Bonds. — The method and the apparatus are described in the preceding article. Become familiar with the devices in the laboratory before trying them on an actual track. Two rails should be provided in the laboratory, connected by a variable resistance; this resistance is to represent various states of a bond, from a perfect contact to a broken bond.

(a) Connect the rails to a D. C. circuit, placing a regulating resistance in series with them, to produce fluctuating currents as in practice.

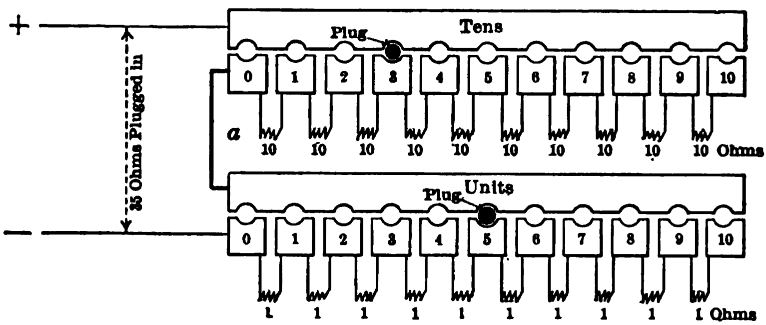

FIG. 19. Decade arrangement of resistances.

(b) Setting the resistance of the bond very low, measure it first with a steady current, then with fluctuating currents.

(c) Repeat the same tests with higher resistances of the bond.

(d) Having become thoroughly familiar with the instrument, measure with it a number of rail bonds on a street-car line in actual operation.

In performing this experiment, pay particular attention to the accuracy throughout its range of the instrument used, and to the influence of current fluctuations. See in how far a poor contact between the rail and the saw blade or the spike used for making contact may affect the results.

25. Plug-Type Wheatstone Bridge. — Series and Decade Arrangement of Coils. — For accurate work, bridges are used in which the three "known" resistance arms R, M, and N (Fig. 10) consist of carefully adjusted resistance coils (Fig. 20). These coils are mounted inside of a box and leads are taken to contacts on its top. Resistances are varied either by inserting plugs, as in Fig. 21, or by dial switches (Fig. 22).

The older method of connecting coils is that shown in Fig. 20; the coils are connected in series, and each plug short-circuits a coil. Thus, in the upper row all the coils are short-circuited, except 4000, 3000, and 200 ohm, the reading being 7200 ohms.

The new or the "decade" method is shown in Fig. 19. Here the resistances which are not in use are simply left out of the circuit. Therefore only one plug is necessary for each decade or row of ten coils.

The advantages of the decade arrangement are:

(1) A smaller number of plugs is required.

(2) Additional resistance between plugs and blocks at the contacts is less.

(3) The result is easier to read, as no summation is necessary.

(4) There is less liability to make mistakes, or to lose a contact plug.

The advantage becomes evident by comparing the two upper rows of contacts in the bridge shown in Fig. 20 with the four rows in Fig. 24. In the first case we have to add mentally

$$4000 + 3000 + 200 + 30 + 20 + 3 + 2 + 1 = 7256 \text{ ohms};$$

in the second case we read directly 6192 ohms. Moreover, in the first case 8 plugs are in the circuit, and 8 more are lying idle on the table. In the second case there are but 4 plugs, and they are always in use.

26. Examples of Plug-Type Bridges. — A simple bridge is shown in Fig. 20; the lettering is the same as in Fig. 10. The bridge has three arms: two ratio arms M and N in the lower row, and the balancing resistance R in the two upper rows of coils. The box is provided with three pairs of terminals — for the battery, for the galvanometer and for the unknown resistance X. The battery key 1 and the galvanometer key 2 are also mounted on the box.

Unlike the slide-wire bridge (Fig. 11), plug-type bridges have only a limited number of ratios $M \div N$, — usually in powers of ten. The balancing is done by the third arm R. In the instrument under consideration, the resistance of this arm may be varied from 0 to 10,000 ohms in steps of 1 ohm. Thus with the ratio $N \div M = 1000 \div 1$, resistances can be measured up to 10,000,000 ohms. On the other hand, by selecting $R = 1$ ohm and $N \div M = 1 \div 1000$, resistances may be measured down to 0.001 ohm. The practical range of the bridge is

within considerably narrower limits, because it is neither sufficiently accurate nor sensitive enough near the apparent limits of its range.

To measure a resistance, connect it to the terminals marked X; select a ratio $N \div M$, say $10 \div 100$. Press the battery key, and then the galvanometer key; vary the resistance R, until the galvanometer remains at zero when its key is pressed. Best results are obtained when the ratio is selected so that balancing can be done with all four places of the resistance R — thousands, hundreds, tens and units. The right ratio $N \div M$ can always be selected, if the approximate

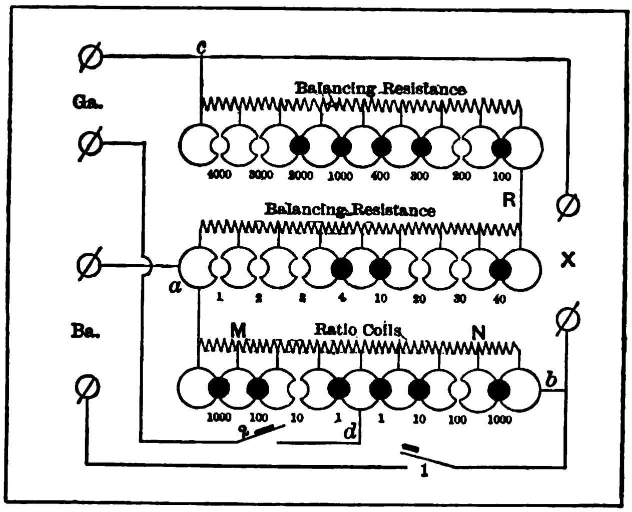

FIG. 20. Diagram of a plug-type Wheatstone bridge.

value of X is known in advance; otherwise, the best ratio is found by trials. With the setting shown in Fig. 20 the unknown resistance

$$X = 7256.\frac{100}{10} = 72560 \text{ ohms.}$$

A Wheatstone bridge for precision work is shown in Fig. 21. The ratio coils M and N are in the last two rows to the right; the other five rows are connected to the balancing resistance R, the decade arrangement of coils being employed. The keys and the binding posts are clearly seen in the sketch. The coils may be joined in series or in multiple or in any combination of series and multiple. The coils may thus be checked against each other in many combinations. For

example, all the ten ohm coils taken in parallel may be compared with any one ohm coil.

The precision of adjustment is $\frac{1}{20}$ per cent for the coils of the tenth ohm series, and $\frac{1}{50}$ per cent for the other coils of the rheostat.

FIG. 21. A plug-type Wheatstone bridge for accurate measurements.

The ratio coils are certified to be like each other within $\frac{1}{100}$ per cent. A similar box is shown in Fig. 22; dial switches being used on the balancing resistance instead of plugs. This makes possible a quicker

FIG. 22. A Wheatstone bridge with dial switches in place of plugs.

adjustment; at the same time, with good workmanship, switch contacts are very little inferior to plugs.

27. Portable Testing Sets. — The above-described bridges are primarily intended for *stationary* work. There is a demand for self-contained *portable* bridges, for locating faults and for other emergency purposes in the operation of electric plants. The Sage ohmmeter described in § 19 is one of this kind. A more accurate instrument is shown in Fig. 23, while its electrical connections may be followed in

FIG. 23. A portable testing set.

Fig. 24. The set consists of a Wheatstone bridge with a decade arrangement of resistances; a galvanometer and a battery of small dry cells are mounted in the same box, so as to make the instrument self-contained.

Some features of this set are as follows:

(1) The terminal marked "Gr." (ground) and the extra blocks *MM* enable the bridge to be used for locating faults according to either the Murray or Varley method (§§ 486 and 487).

(2) The instrument may be used as an ordinary resistance box.

(3) The galvanometer may be used separately, or in series with a resistance, for any desired purpose.

(4) If the battery is exhausted, or not strong enough for a certain purpose, the flexible leads may be disconnected and an outside battery connected to the bridge.

(5) An outside galvanometer may be used if desired, by disconnecting the flexible galvanometer leads.

Explicit directions are supplied with the instrument, so that any

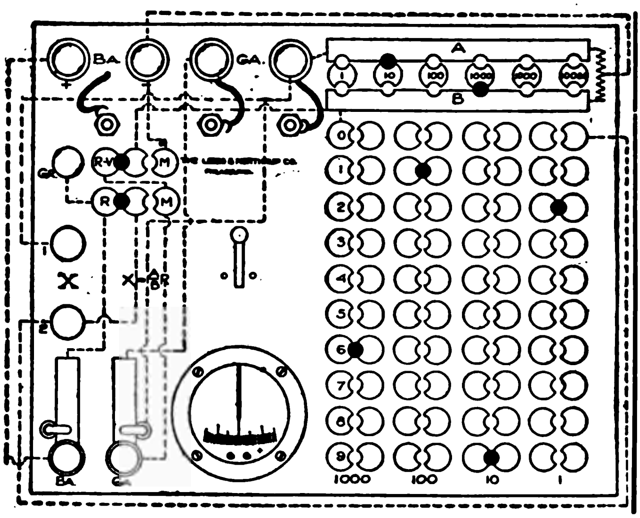

FIG. 24. The diagram of connections of the testing set shown in Fig. 23.

one with a very elementary knowledge of electricity can use it. Similar testing sets are made by other leading manufacturers of measuring instruments.

28. EXPERIMENT 1-L. — Measuring Resistances with a Plug-Type Wheatstone Bridge. — A few types of bridges are described in §§ 25 to 27. The problems which may be solved with these bridges are the same as enumerated in § 16. If possible the student should connect the coils of the bridge itself in various combinations, so as to check them against each other. The purpose of the exercise is not only to learn how to perform measurements, but also to study the bridge itself, ascertaining the limits of its accuracy, the best range, the necessary sensitiveness of the galvanometer, etc.

29. Measurement of very Small Resistances. — The Wheatstone bridge is not suitable for measuring small resistances, say below 0.1 ohm, because the resistance of the contacts at a, b, c and d (Fig. 10) may constitute an appreciable part of the resistances X and R themselves. The drop-of-potential method (§ 2) gives satisfactory results with resistances considerably below 0.1 ohm, if care is taken to have voltmeter leads properly applied, so as to eliminate the contact resistance (Fig. 35). For an accurate comparison of very low resistances, the potentiometer method may be used (see § 43).

Lord Kelvin combined the Wheatstone bridge and the drop-of-potential method into a scheme which is exceedingly accurate for measuring low resistances, say down to 0.0001 ohm. The diagram of connections of this so-called Kelvin double-bridge is shown in Fig. 25.

The resistances R and X to be compared are connected in series with a low-voltage battery *Ba.*, and some regulating resistance not shown

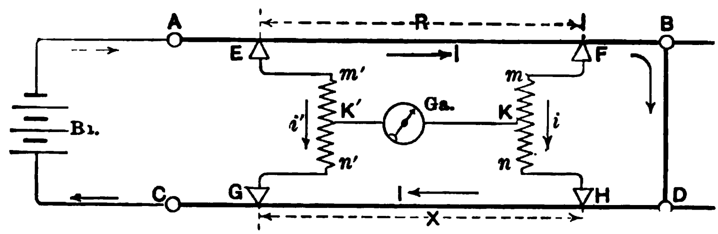

FIG. 25. Principle of the Kelvin double-bridge.

in the Figure. The connections to the galvanometer are taken from the points E, F, G and H separate from the main terminals. This is a point of paramount importance, because the contact resistances at A, B, C and D should not enter into the result. Four ratio coils are used, m, n, m' and n', instead of two ratio coils M and N of the ordinary Wheatstone bridge (Fig. 10).

The unknown resistance X is measured by adjusting either R or the ratio coils, until the galvanometer gives no deflection. Both pairs of ratio coils are adjusted simultaneously, so that the relation

$$m + n = m' \div n' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

is preserved all the time. When the balance is obtained the relation holds true

$$R \quad X = m + n = m' \div n' \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

from which X is calculated.

Proof: When no current flows through the galvanometer, the points K' and K are at the same potential. Therefore the voltage drop from E to K' is the same as from F to K. With the notations in the sketch we have

$$i'm' = IR + im.$$

The same holds true with respect to the point G; hence,

$$i'n' = IX + in.$$

From these two equations we get

$$R : X = (i'm' - im) + (i'n' - in),$$

or substituting for m' its value from (1) we obtain after a simple transformation the relation (2).

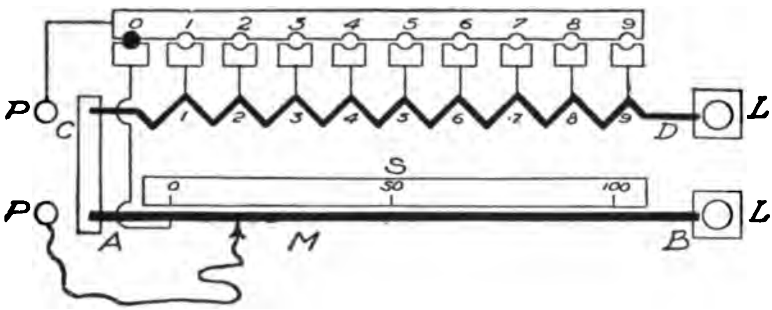

FIG. 26. Leeds and Northrup variable low resistance, for use as a standard in connection with the Kelvin double-bridge.

There are two types of Kelvin bridge: (1) Either a set of a few standard resistances R are supplied with the bridge, and the adjustment is made by the ratio coils; or (2) the ratio coils are made to give only a limited number of combinations, but the standard resistance R is made adjustable, so as to give practically any value of resistance within certain limits. The first is the older method, the second is coming into use.

The variable standard low resistance made by the Leeds and Northrup Co. for use with the Kelvin double-bridge is shown diagrammatically in Fig. 26.

AB is a heavy piece of resistance metal of uniform cross-section and uniform resistance per unit of length; CD is another piece of resistance metal of smaller cross-section, and the two are joined together by a heavy copper bar AC into which both are silver-soldered; LL are the current terminals and PP are the potential terminals. The resistance

of AB between the marks 0 and 100 on the scale S is .001 ohm. From the point 1 on the resistance CD to 0 on AB is also .001 ohm, from 2 to 0 is .002 and so on, and from 10 to 0 is .01 ohm. The slider M moves along the resistance AB and its position is read on the scale S which is divided into 100 equal parts and can be read by a vernier to thousandths. Subdivided in this way the resistance between the tap-off points PP may have any value from .001 to .01 ohm by steps of .000001 ohm. Using a ratio of 1 to 10 it gives all values from .1 ohm to .01 ohm, by steps of .00001 ohm, and, using the inverse ratio, all values from .001 ohm to .0001 ohm by steps of .0000001 ohm.

It will be noted that there are no contacts in the main circuit between the terminals LL. The only contacts are at the tap-off points to the potential terminals PP. The resistance of these contacts is negligible, being in series with the ratio coils, which have several hundred

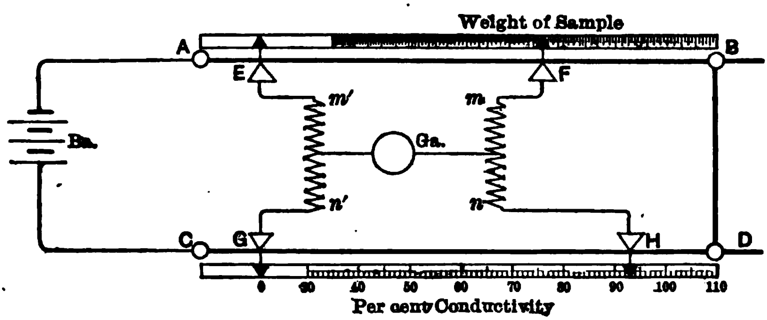

FIG. 27. Diagram of the Hoopes conductivity bridge.

ohms resistance. The ratio coils are mounted within ordinary resistance boxes, similar to the one shown in Fig. 21; the resistances may be adjusted to agree with each other within $\frac{1}{100}$ per cent.

30. Hoopes Conductivity Bridge.—The principal practical application of the Kelvin double-bridge is for determining conductivity of bars of copper and aluminum. This is done regularly in factories manufacturing wire for electrical purposes; wire is also tested by large consumers before accepting a consignment. It is desirable in such cases to modify the standard Kelvin bridge described in the preceding article, so as to fulfill the following requirements:

(1) The apparatus must be direct-reading in per cent conductivity of chemically pure metal, instead of giving results in ohms.

(2) The apparatus must be adapted for testing a large number of similar samples in a short time.

(3) It must be easily handled by a person who has but little electrical knowledge.

A bridge which satisfies these conditions was designed by Mr. Wm. Hoopes. It is shown diagrammatically in Fig. 27; a general view of the apparatus is given in Fig. 28. Comparing Figs. 27 and 25 it will be seen that the electrical connections in the Hoopes bridge are identical with those in the regular Kelvin bridge. AB is a standard wire made of the same material as the samples to be tested, in order to have the same temperature coefficient; CD is a sample under test. The operations for determining per cent conductivity are very simple. The sample wire is cut off to the standard length of 25 inches in a special cutting-off machine, and accurately weighed. Then it is clamped in the position CD and the contact F set at a place corresponding to the weight of the sample. The contact H is moved back and forth until the galvanometer shows zero; per cent conductivity is then read off directly on the lower scale.

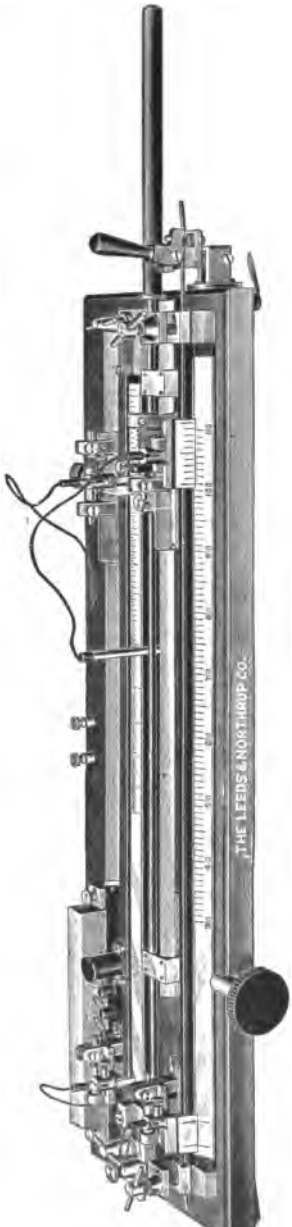

FIG. 28. The Hoopes conductivity bridge.

The theory of the method is easily understood from the fact that a sample of a certain metal, of a given length and weight, has a definite and known resistance if chemically pure (100 per cent conductivity). Therefore the scale of the standard wire may be made so as to balance a chemically pure sample with H on the division 100 of the lower scale. Then if the sample under test has a lower conductivity, a smaller length of it balances the standard wire, and the slide H has to be moved to the left. The decrease in length is evidently directly proportional to the decrease in conductivity. Therefore the lower scale may be calibrated directly in per cent.

The upper scale could be calibrated in circular mils, instead of weights; but it is easier to determine the weight of a piece of wire 25 inches long,

than its average cross-section. A single standard wire covers with some overlap a range of three numbers of the Brown and Sharp scale; if a wider range is required several standards are used. Each standard with its scale is mounted on a separate piece of hard rubber, and may easily be clamped in place.

The details of the bridge may be seen in Fig. 28. The standard conductor is shown in the back and the two contacts on it are made by means of knife edges; one remains set at the zero position and the other slides up and down, so as to take any position on the scale. By a special locking device, the latter is arranged so that it cannot be moved along the standard except when the knife edge is raised. This is arranged to prevent wear on the standard. The sample wire is clamped in the front and also has two knife edges making contact on it, one at the zero position, which remains fixed, and the other at the other end, which is movable. Wires which are not perfectly straight can be stretched straight by means of the device shown at the right-hand end. The long rod also projecting from the right-hand end is used to give large movements to the contact knife edge, and the handle projecting from the front towards the other end works a rack and pinion which gives it small movements.

31. EXPERIMENT 1-M. —Measurement of Low Resistances with Kelvin Double-Bridge.—See §§ 29 and 30.

32. EXPERIMENT 1-N —Determination of Conductivity and of Temperature Coefficient of Wires with Kelvin or Hoopes Double-Bridge. —See §§ 29 and 30.

33. Other Methods of Measuring Resistances. —Three methods of measuring electrical resistances are described in this chapter: The drop-of-potential method, the substitution method and the Wheatstone bridge. Some other methods are used under special conditions; as such may be mentioned the direct-deflection method described in §§ 481 and 483, and the direct-reading ohmmeter described in § 482.

CHAPTER II.

AMMETERS AND VOLTMETERS—CONSTRUCTION AND OPERATION.

34. In dealing with electrical energy two of the most important quantities to be measured are: *current,* and *difference of potential.* Commerical instruments for measuring electric current are commonly called *ammeters,* because the practical unit of electric current is the "ampere." Instruments for measuring differences of potential, or electric pressures, are called *voltmeters,* since the practical unit of difference of potential is the "volt."

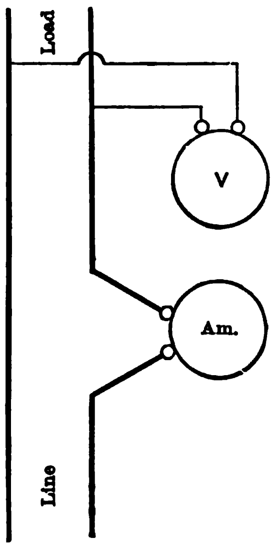

Fig. 29. Standard connections for a voltmeter and an ammeter.

Ammeters are connected in series with the circuit in which the current is to be measured (Fig. 29); voltmeters are connected at two points of the circuit, between which it is desired to determine the difference of potential. There is no fundamental difference in the construction of ammeters and voltmeters, for — with the exception of electrostatic voltmeters — all voltmeters are in reality ammeters calibrated in volts. In other words, they measure current passing through them, which current is made proportional to the voltage at the terminals of the instrument, and the scale is divided directly in volts.

To illustrate, suppose that an ammeter of a high resistance, say 1000 ohms, be connected *across* a line and that it show 0.1 ampere. According to Ohm's law it takes 100 volts to drive 0.1 ampere through a resistance of 1000 ohms; therefore the voltage of the line is 100 volts. To use the instrument as a voltmeter, the scale may be conveniently changed so as to have the division "100 v." correspond to what was formerly "0.1 amp."

DESCRIPTION OF COMMERCIAL TYPES.

35. Ammeters and voltmeters are built on various principles, as enumerated below; each system having its advantages and shortcomings, and a field of application of its own. Some instruments may be used with both direct and alternating currents; others are suitable for one kind of current only. The types in practical use at present are:

(1) Soft-iron core, or electro-magnetic instruments, based on the attraction between a stationary coil and a pivoted piece of soft iron (Figs. 30 and 32).

(2) Moving-coil instruments in which a light coil moves in the strong field of a permanent magnet (Figs. 33 and 34).

(3) Electro-dynamometer type instruments, based on the attraction between a moving and a stationary coil (Figs. 38 and 39).

(4) Hot-wire instruments, in which the current to be measured heats a wire, thus changing its length (Figs. 41 and 42).

(5) Induction-type instruments, based on the principle of revolving magnetic field (Fig. 43).

(6) Electrostatic voltmeters (Figs. 46 and 47) in which two metallic plates are mutually attracted because of opposite electric charges on them.

These types are described more in detail in the following articles.

36. Soft-Iron Instruments. — (*a*) One of the oldest instruments of this type is shown in Fig. 30. *C* is a stationary coil; *P* is a soft-iron plunger pivoted so that it can move freely up and down. The shaft which supports the plunger also carries the counter-weight *Q* and the pointer *N*. When a current flows through the coil, the plunger is drawn in, against the effect of the weight *Q*. The corresponding deflection is shown by the pointer on the scale. When the circuit is opened, the counter-weight brings the moving system back to zero.

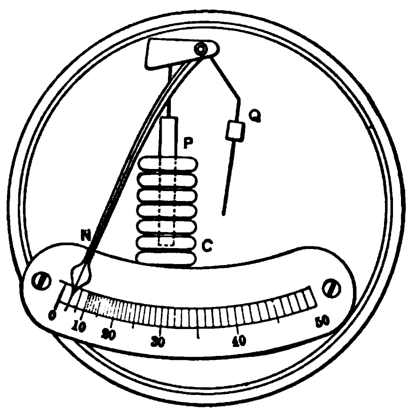

FIG. 30. Plunger-type soft-iron instrument.

In instruments of this kind used as ammeters, the coil consists of a few turns of heavy wire; in voltmeters it has a great many turns of fine wire. Even then the

resistance of the coil is not sufficient to cut down the current, and it is necessary to have some resistance R (Fig. 31) connected in series with the instrument. This resistance is usually called the multiplier; by varying the resistance of the multiplier, the range of the instrument may be changed within wide limits.

Soft-iron instruments may be used on alternating as well as on direct current, because the attraction between soft iron and a coil does not depend on the direction of the current. In instruments intended for alternating current circuits the plunger is laminated, or made of iron wires; this is done to prevent the formation of eddy currents and subsequent heating (§ 169). The spool on which the coil is wound must be made of an insulating material, or, if made of metal, must be subdivided so that no secondary currents can be induced in it. The calibration of the same instrument is somewhat different on alternat-

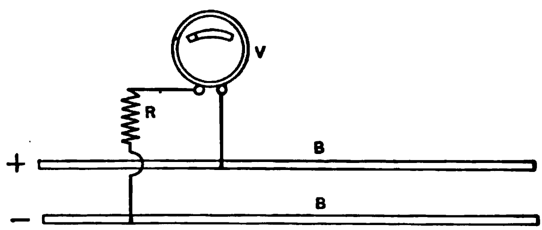

FIG. 31. The use of a voltmeter multiplier.

ing and on direct current, because of the influence of hysteresis, eddy currents and saturation in the plunger; the calibration also depends to some extent on the frequency and on the wave-form of the alternating current.

(*b*) A more perfect instrument of the same type, the so-called *Thomson inclined-coil ammeter*, is shown in Fig. 32. The coil is placed at about 45 degrees to the direction of the shaft; a piece of soft iron (iron vane) is mounted on the shaft in an inclined position. When the coil is energized, it produces a magnetic flux, as indicated by the arrows; the vane tends to move so as to embrace a maximum of lines of force. In doing so it turns the shaft, and the deflection is shown on the scale. The motion is opposed by a spiral spring, the counter-weight serving to balance the moving part.

This instrument is more compact than the above-described plunger-type instrument; the moving part is lighter, and the friction is much reduced, making the instrument more sensitive. Moreover, the spring control is more positive than the gravity control used in the plunger instrument. Thomson inclined-coil instruments are made practically

"dead-beat" by means of an aluminum vane fastened to the moving part. The movement is effectively damped by the resistance of the air to movements of this vane, and the pointer assumes its final deflection without swinging to and fro.

(*c*) By saying that an ammeter indicates an alternating current it is understood that it merely shows its effective value, and not instantaneous values. Let I be a certain value of direct current flowing through the coil of a soft-iron instrument, and M the corresponding

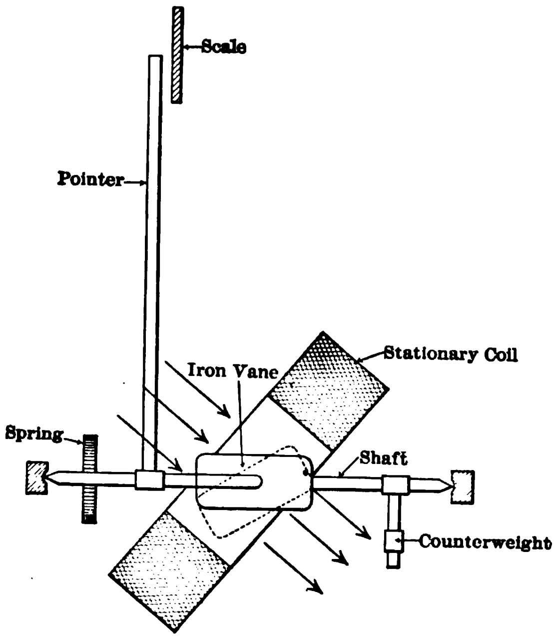

FIG. 32. Mechanism of the Thomson inclined coil ammeter.

magnetic flux in the plunger. The pull on the plunger is proportional to the product of the current times the flux, or

$$\text{pull} = I \times M \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The magnetism in the plunger is produced by the current I; if the saturation in iron is not carried too high, it may be assumed, that $M = kI$, where k is a constant; so that

$$\text{pull} = k \, . \, I^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

In other words the pull is proportional to the square of the current. If an alternating current now flow through the coil and i and m be some instantaneous values of the current and of the flux, we have

as before, that the instantaneous pull $= ki^2$. It is easy to see that the direction of the pull does not change with the change in direction of the current, because i and m change their sign simultaneously.

Since the inertia of the moving part of the instrument is sufficiently large to prevent it from following the fluctuations in the value of the pull, the plunger assumes the position corresponding to the average pull. Thus we have

$$\text{average pull} = k \cdot \frac{1}{T}\int_0^T i^2 \cdot dt = k \cdot I^2_{\text{eff}} \quad . \quad . \quad . \quad . \quad (3)$$

where dt is an infinitesimal element of time, and T is the duration of one cycle of the alternating current.

The value of I_{eff}, defined by the expression (3) is called the *effective* value of the alternating current, or the square root of the mean square of the instantaneous values. It will be seen by comparing the expressions (3) and (2) that a soft-iron instrument calibrated with direct current should show effective values of alternating currents. In reality this is not quite true, because the magnetism M is not exactly proportional to the current (effect of saturation in iron); moreover the effect of hysteresis and of eddy currents is noticeable. At any

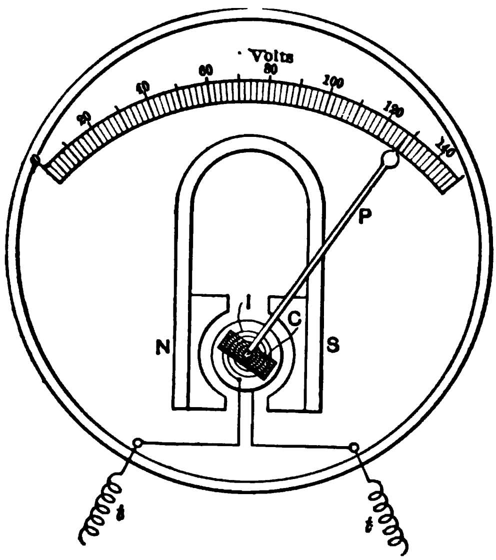

FIG. 33. Arrangement of parts in a moving-coil instrument.

rate, a calibration made with direct current (with reversed readings) is true within a very few per cent with alternating currents.

37. Moving-Coil Instruments.—The principle upon which these instruments are constructed will be seen from Figs. 33 and 34. A

light coil *C* of fine wire is pivoted or suspended in the strong field of a stationary steel magnet *NS*. When a direct current is passed through the coil, it tends to move so as to embrace the lines of force produced by the magnet, according to the fundamental law of electro-magnetism. The deflection is shown on the scale by the pointer *P*. A soft-iron cylinder *I* is placed inside the coil. It offers an easier path for the lines of force from pole to pole, and also makes the field in the air-gap uniform. This latter point is of particular importance, since

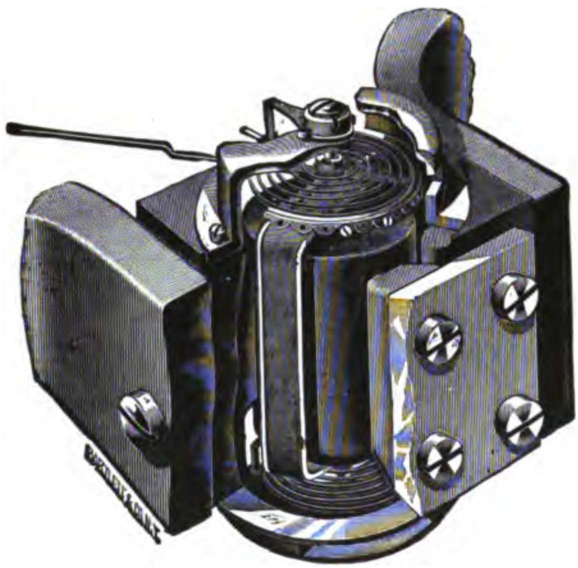

FIG. 34. Construction of Weston moving-coil instruments.

it makes it possible to have a perfectly uniform scale, which is one of the good features of these instruments.

The movement of the coil is opposed by two spiral springs, one on top and the other on the bottom (Fig. 34); the springs are coiled in opposite directions so that one of them is twisted while the other is untwisted during the movement of the coil. This compensates for a possible non-uniformity in the material of the springs. In most instruments, the same springs are used for leading the current into and out of the coil. In some cases separate leads are used independent of the springs; such leads must offer no opposition to the movement of the coil. Without the controlling force of the springs, the needle would be deflected to the end of the scale with any current.

It is easy to see that instruments with permanent magnets can

be used for direct current only, because the direction of deflection depends upon the direction of the current. When an instrument of this type is connected to an alternating-current circuit, the needle merely trembles at its zero position without giving any deflection. This is because it receives opposite impulses in such rapid succession that it has no time to move in either direction.

Moving-coil instruments are easily made "dead-beat" by winding the moving coil on an aluminum frame. Eddy currents induced in the frame during the movement of the coil effectively check any tendency to swing about the point of equilibrium. In some makes of instruments of this type the damping is claimed to be so adjusted that the pointer passes a little beyond the final position and immedi-

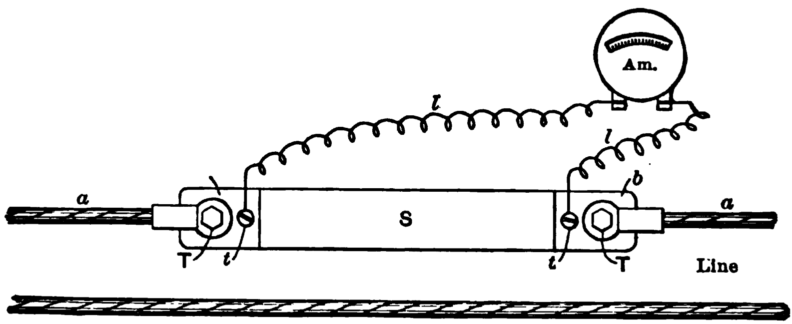

FIG. 35. Measurement of currents with an ammeter shunt and a milli-voltmeter.

ately returns to it. The supposed purpose of this arrangement is to make sure that the movement is not impeded by friction.

The moving coil carries only very small currents — usually not more than 0.02 amp.; at the same time the resistance of the coil is comparatively low. Therefore instruments used as voltmeters are provided with high resistance multipliers connected in series with the coil (Fig. 31). These multipliers are either mounted within the case of the instrument itself, or else are placed outside the instrument in separate boxes.

38. Ammeter Shunts. — Moving-coil instruments used as ammeters are provided with so-called "shunts" which carry the main current to be measured. The shunt is connected into the line *aa* (Fig. 35) in which it is desired to measure current. The instrument (Am.) itself is but a sensitive voltmeter (milli-voltmeter) which measures the drop across the terminals *tt* of the shunt.

Assume, for instance, that the resistance of the shunt is 0.001 ohm,

and that the instrument reads 50 milli-volts, or 0.050 v. According to Ohm's law the current in the line

$$i = \frac{0.050}{0.001} = 50 \text{ amperes.}$$

In commercial instruments, the shunt and the milli-voltmeter are usually calibrated together, and the scale reads directly in amperes instead of in milli-volts. In ammeters not over 25 amperes capacity, shunts may be placed inside of the ammeter case, so as to make the instrument self-contained. In larger instruments, the shunt is placed

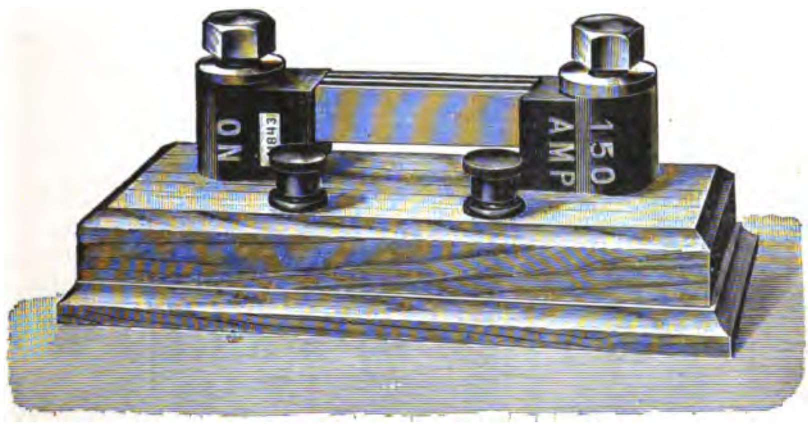

FIG. 36. An ammeter shunt (Weston).

outside (Fig. 36) and connected to the milli-voltmeter by flexible leads.

Ammeter shunts are made of strips of manganin, German silver or other material of high specific resistance and low temperature coefficient. The strips *S* (Fig. 35) are sweated into heavy brass blocks *bb*. Two separate pairs of terminals are provided: Large terminals *TT* for the line connection, and small terminals *tt* for connecting the shunt to the milli-voltmeter. The latter terminals are placed so as to measure the drop across the body *S* of the shunt, independent of the distribution of current in the blocks *bb*. This distribution may vary with an uncertain contact at the main terminals *TT*.

One common mistake which the beginner is apt to make, when using moving-coil instruments, is to forget to connect a multiplier or a shunt. This invariably results in either the moving coil (Fig. 34) or the spiral springs being burned out, and the pointer being bent or broken.

39. Friction in Pivots.—The usual way of supporting the moving coil is by means of hardened steel pivots with sharp points; these rest in *V* or cup-shaped depressions formed in agate or sapphire bearings. While the moving system is made as light as possible, the area of contact between the end of the pivot and its journal is so minute, that the pressure per unit area is quite considerable, even with the instrument at rest. As a result some wear is produced and the friction increases with time, especially if the instrument is carried around or is subjected to continuous jar.

While such conical pivots are standard with most makers, there is a tendency on the part of a few to remedy the drawback of sharp points. One company tried to use, though without success, highly polished cylindrical pivots in which sharp points were eliminated and the pressure per unit area considerably reduced.

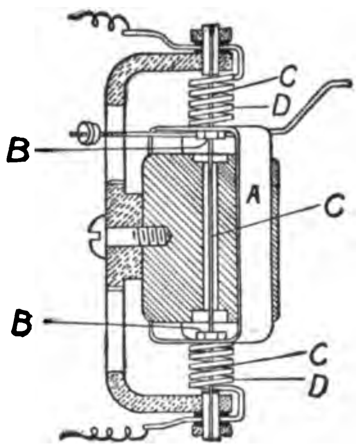

FIG. 37. Construction of Whitney moving-coil instruments; the coil is supported by the springs *DD*, instead of on pivots.

Another solution is shown in Fig. 37. Two ruby jewels *BB*, of the kind used in watches, are attached to the moving coil *A* of the instrument. Through the holes pierced through these two jewels is threaded a length, *CC*, of phosphor bronze or nickel steel wire, which thus guides the coil and holds it truly centered. To provide against endwise motion, spiral springs, *D*, *D*, are attached to the coil, the other ends of same being secured to brackets on a stationary portion of the instrument. These springs not only support the coil but furnish the force opposing its rotation when current flows. If an instrument so built is dropped, the coil, *A*, evidently will but slide up and down on its guide wire for a short distance without causing any damage. When in use and at rest, the coil moves as freely as that of a reflecting galvanometer, the only friction being the molecular one of the supporting springs.

40. Electro-Dynamometer Instruments.—These instruments have a stationary and a movable coil; the two coils being connected in series attract each other when a current flows through them (Figs. 38 and 39). Spiral springs used as the controlling force for the movable coil hold it at a certain angle with the stationary coil when no current is flowing. When a current is flowing through the coils, the moving coil

tends to place itself in a plane parallel to that of the stationary coil, producing a deflection which is read on the scale.

The coils of a voltmeter based on this principle are shown in Fig 38; the general make-up of the instrument is the same as in Fig.

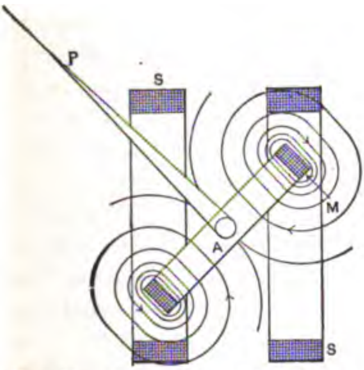

FIG. 38. Arrangement of coils in a dynamometer-type voltmeter.

34, except that stationary coils are substituted for permanent magnets. Because of this latter fact, the instrument becomes equally applicable for direct or alternating current, since — the coils being connected in series — the current changes simultaneously in both, and the attraction between them does not reverse. In fact, electro-dynamometer type instruments are calibrated with direct current and used on alternating currents.

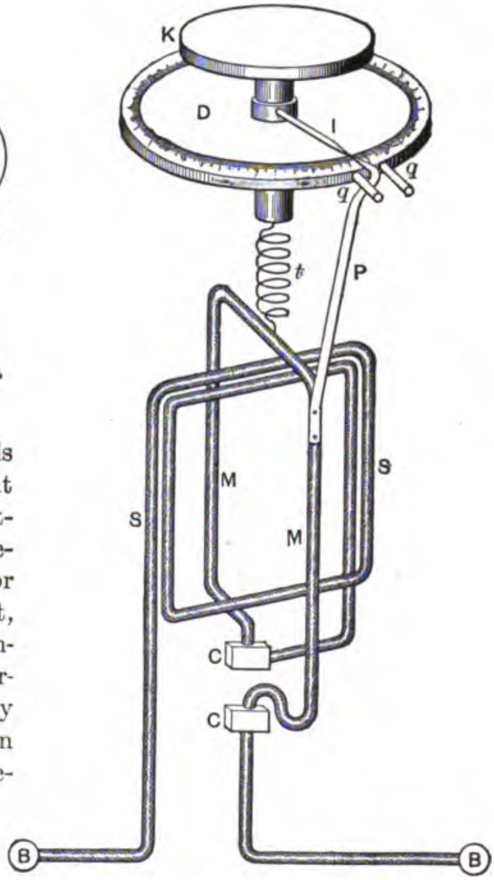

FIG. 39. Arrangement of parts in an electro-dynamometer (ammeter).

Instruments of this type are better adapted for voltmeters than for ammeters. In the latter, it is difficult to devise a satisfactory arrangement for leading heavy currents into the movable coil without interfering with its free motion. The usual construction where large currents are to be measured is shown in Fig. 39. *BB* are the terminals of the instrument; the current flows from the left terminal through the stationary coil *SS* to the upper mercury cup *C*; thence through the

movable coil MM and the lower cup C to the right terminal B. The coil MM is suspended from the top of the instrument by a cocoon thread (not shown in Fig. 39), and is controlled by the spiral spring t operated by the torsion knob K; the zero of the scale is between the stops qq. When a current flows through the instrument the pointer P strikes against the right stop q. The knob K is then turned to the left, until P comes back to zero. The index I shows the angle of torsion on the dial D. Fig. 40 gives the general view of an electro-dynamometer.

FIG. 40. An electro-dynamometer.

The instruments shown in Figs. 39 and 40 are not direct reading, the pointer indicating an angle only. If α is the angle of torsion in degrees, the current

$$i = k\sqrt{\alpha},$$

where k is a calibration constant of the instrument. This formula is deduced as follows: The torque between the two coils is proportional to the product of currents in them, or

$$\text{torque} = k_1 \cdot i_{sta} \cdot i_{mov}.$$

The coils being in series $i_{sta} = i_{mov} = i$; therefore

$$\text{torque} = k_1 i^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

This torque is balanced by the torsion of the spring; the spring is wound so that the twisting force is proportional to the angle of torsion Thus

$$\text{torque} = k_2\alpha,$$

hence

$$k_1 i^2 = k_2\alpha,$$

or

$$i = \sqrt{\frac{k_2}{k_1} \cdot \alpha} = k\sqrt{\alpha}.$$

With alternating currents the expression (4) becomes:

$$\text{torque} = k_1 \cdot \frac{1}{T}\int_0^T i^2 dt = k_1 \cdot I^2_{eff}.$$

Hence the instrument shows true *effective* values of alternating currents (see § 36 *c*).

A good feature of electro-dynamometers used as ammeters is that they are accurate and sensitive; moreover, they may be calibrated with direct current and used with alternating current. Their serious drawback is that they are not direct reading and cannot be used on commercial switchboards. The presence of mercury, and the necessity for leveling make electro-dynamometers inconvenient to handle, even in ordinary testing work. Moreover, they have no provision for damping, and require some skill in taking readings, especially with fluctuating currents.

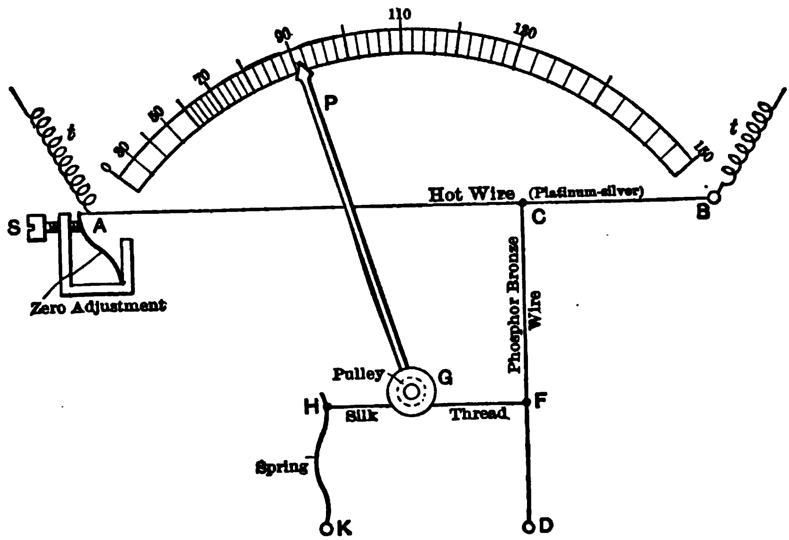

FIG. 41. Mechanism of Hartmann & Braun hot-wire instruments.

In spite of these drawbacks, they are largely used in testing, for lack of better A. C. ammeters. Attempts have been made to make the electro-dynamometer direct reading in order to do away with the awkward expression $\sqrt{\alpha}$. To make the scale more regular the moving coil is placed eccentrically, and both coils are bent in such a way as to increase deflections with small currents.

41. Hot-Wire Instruments. — A typical hot-wire instrument is shown in Fig. 41. The current to be measured, or a definite part of it, passes through the stretched platinum-silver wire AB and heats it so that it takes an appreciable sag. The resulting downward motion of the point C is transmitted to the pointer P. The deflection is

magnified by the wire CD the point F of which is under the tension of the spring KH. When C moves downward, F and H move to the left, and the silk thread turns the pulley G; the pointer P, mounted on the same shaft with G, shows the deflection on the scale. Instruments of this construction can be used equally well with direct or alternating currents, as an ammeter, or as a voltmeter. Shunts are used with hot-wire ammeters (see Fig. 35); the current through the hot wire itself being usually about 5 amperes with a full scale deflection. The scale of hot-wire instruments is not uniform, because the heat energy put into the wire increases as the square of the current.

The instrument shown in Fig. 41 is made "dead-beat" as follows: An aluminum disk is mounted on the same shaft with the pulley G and placed between the poles of a strong horse-shoe magnet. Eddy currents are induced in the disk during its motion and effectually damp vibrations of the needle.

The hot-wire instrument shown in Fig. 42 has the following construction: a wire, *a-b*, of high resistance, low temperature coefficient and non-oxidizable metal, is secured at one end to a plate *c* and passed around a pulley *d* which is fastened to a shaft *e*. The other end of the wire is brought back again and mechanically — though not electrically — attached to the same plate *c*. Plate *c* is kept under stress by the spring *f*, which constantly tends to pull it in a direction at right angles with the axis of the shaft *e*; the plate is so guided that it can be moved in that one direction only. To the shaft *e* is likewise secured an arm *g*, bifurcated at one end and counterweighted at the other. Between the extremities of the bifurcated ends of the arm *g* is another shaft *h*, on which there is a small pulley and to which is attached the needle *i* that gives the desired indications. A fine silk fiber is attached at one end to one of the arms of *g*, then passes around the pulley on the staff *h* and has its other extremity secured to the other arm. The arms are springy and serve to keep the silk fiber taut. The current to be measured flows through the wire *a* only, entering and leaving as indicated by the arrows.

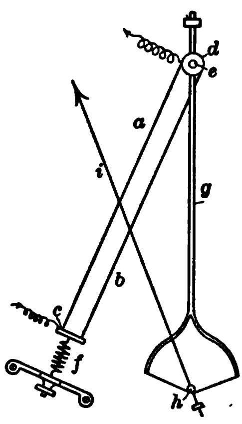

FIG. 42. Mechanism of Whitney hot-wire instruments.

When *a* is heated by the passage of a current, it expands; this makes *a*'s tension relatively less than that of *b*; the equilibrium can be restored only when the pulley *d* rotates sufficiently to again equalize the strain.

In its rotation, d carries g with it, and g in moving causes the silk fiber to rotate the shaft which carries the needle. If the temperature of the air surrounding the instrument changes, a and b are affected alike; their resulting equal expansion simply causes a movement of the plate c back or forth in its path without any tendency to rotate the pulley.

If r is the resistance of the "hot-wire," the *average* heat generated in it with alternating currents is

$$\frac{1}{T}\int_0^T (i^2 r)\, dt = r \cdot \frac{1}{T}\int_0^T i^2 \cdot dt = r\, I^2_{\text{eff}}.$$

Hence, a hot-wire instrument calibrated with direct current shows true effective values of alternating current (see § 36 c).

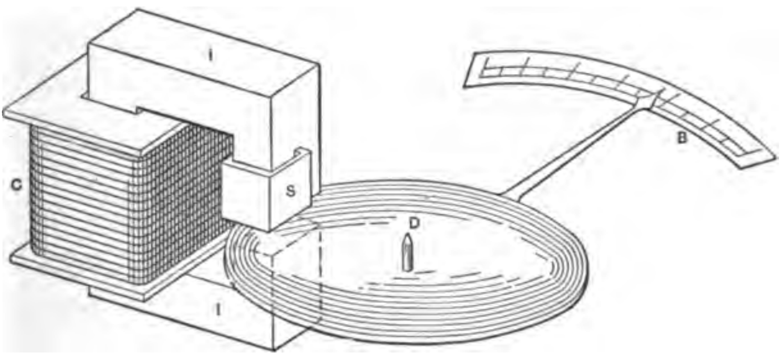

FIG. 43. Principle of action of Westinghouse induction-type instruments.

42. Induction-Type Instruments. — These instruments are based on the principle of a revolving magnetic field produced by two out-of-phase alternating currents (see § 332). In the construction shown in Fig. 43 the alternating current to be measured flows through the coil C of the laminated iron core I and produces in it a pulsating magnetic field. A pivoted aluminum disk D is subjected to the inductive action of this field in the air gap of the core; which disk can be made to move under the influence of eddy currents induced in it, if these currents are *unsymmetrical* in respect to the iron core. This is done by placing an electric screen, or a secondary coil S, on *one side* of the iron core. The currents induced in this coil oppose the primary currents in C and thus weaken the magnetic flux on one side of the core — the phase of the flux is also changed hereby. This combination of the two fluxes produces unsymmetrical currents in the aluminum disk and causes it to move, thus producing a deflection on the scale B against the action of spiral springs, used as the controlling force. In short,

this instrument is a single-phase induction motor, the screening coil taking the place of a "split-phase" arrangement. In more recent instruments an aluminum drum is used as the moving part, instead of the disk. The instrument has then the aspect shown in Fig. 83; however, the theory remains the same.

The instruments based on this principle are robust, convenient for use, and possess a fair degree of accuracy. Of course, they can be used on alternating currents only, and their indications depend to a considerable degree on the frequency of the supply. It is possible to have in these instruments a fairly uniform scale extending over 300 degrees, which adds considerably to their accuracy.

Ammeters based on this principle are usually wound for 5 amperes,

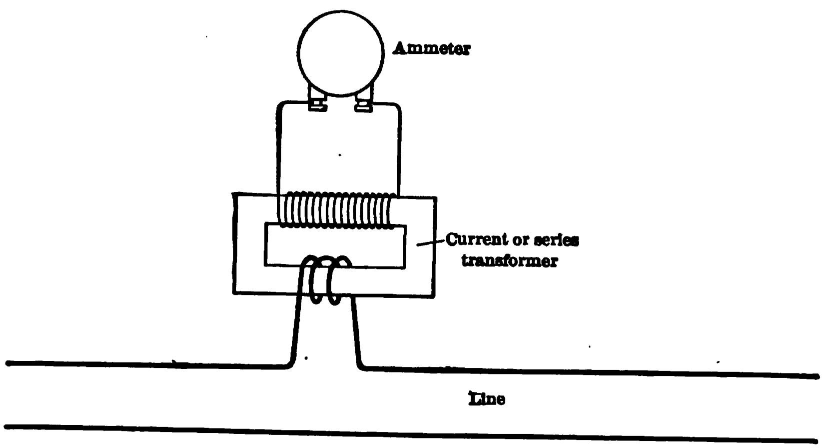

Fig. 44. Measurement of alternating currents through a series- or current-transformer.

and adapted for use in connection with series or current transformers (Fig. 44) by means of which currents of any value can be measured with the same instrument. Voltmeters are provided with multipliers, and for higher voltages also with shunt transformers (Fig. 45).

One detail in induction-type voltmeters deserves special mention. When the temperature of the aluminum disk increases, its resistance is increased, thereby decreasing the current flowing in the disk. This reduces the torque, and consequently the deflection of the pointer. Two methods are used for compensating the influence of temperature, by increasing the strength of the magnetic field:

(1) In meters intended for high frequencies, and having a large torque, a short-circuited coil is placed around one pole of the electromagnet *II* (Fig. 43). This coil acts as the secondary of a transformer,

and reduced the flux in the instrument. When the temperature increases, the resistance of this coil also increases; this reduces its choking effect on the magnetic field, and the flux increases.

(2) In meters for low frequencies a non-inductive resistance is shunted around the magnetizing coil C (Fig. 43). This shunt is selected of such a value that its resistance increases with temperature at the same rate as the resistance of the aluminum disk. Therefore, when the temperature rises, more and more current flows through the magnetizing coil of the voltmeter, increasing the field strength in the desired proportion.

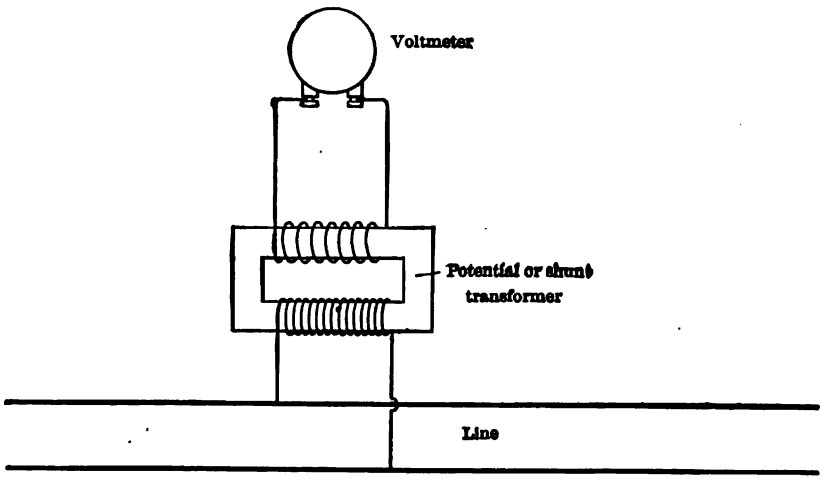

FIG. 45. Measurement of alternating voltages through a potential- or shunt-transformer.

43. Electrostatic Voltmeters. — These instruments are based on electrostatic attraction between two plates carrying opposite electric charges. The stationary and the moving plates are clearly seen in the voltmeter shown in Fig. 46. They are insulated from each other and are connected to opposite sides of the line, so that they are charged with equal and opposite quantities of electricity. The movable plate is attracted by the stationary, and the deflection is shown on the scale. In this particular instrument gravity is used as the controlling force. By changing the weights shown on bottom of the movable plate, the sensitiveness of the instrument is varied within wide limits. Electrostatic voltmeters give identical deflections with direct and with alternating voltages; in the latter case the sign of the electric charges is changed simultaneously on both plates, so that the force between them is always an attraction.

With low voltages the necessary area to be given the plates becomes rather large, in order to have an appreciable attraction. For this reason, electrostatic voltmeters are mostly used for high-tension work. A low-voltage static voltmeter designed by Lord Kelvin is shown in Fig. 47. The required surface is obtained by using several small plates, because of which the instrument is known as the *multi-cellular* voltmeter.

An ingenious electrostatic voltmeter, designed by Mr. S. M. Kintner

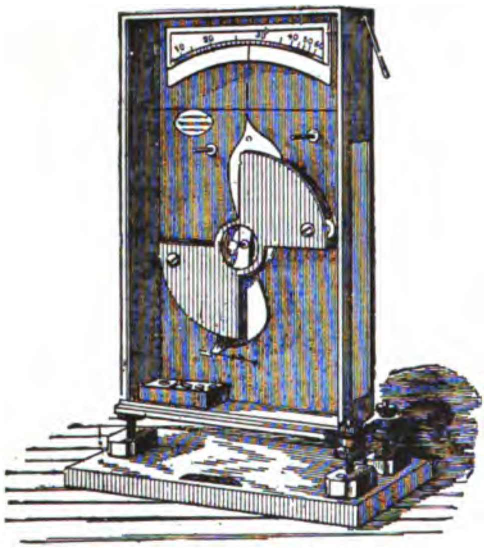

FIG. 46. Lord Kelvin static voltmeter for high voltages.

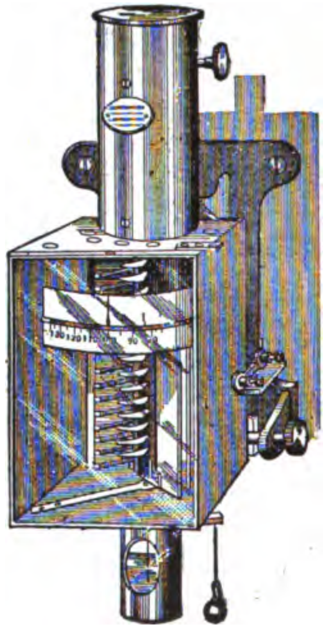

FIG. 47. Lord Kelvin multi-cellular (static) voltmeter for medium and low voltages.

is shown in Fig. 48. The working parts of the instrument are immersed in insulating oil, and the voltmeter may be built for voltages up to 200,000 volts. The stationary part consists of two curved plates *BB* connected to the lines, either directly or through the condensers *CC*. The moving element consists of two suspended hollow cylinders *MM*. The instrument may be used with both condensers in series, or with either or both short-circuited, thus giving a wide range of voltages. When an electric pressure is applied between the plates *BB*, the moving element becomes charged by induction, and its cylinders tend to approach the stationary plates. This they can do by moving counter-clock-wise, the shape of the stationary plates being such that this

movement reduces the distance between them and the moving element. The deflection is read on the scale, spiral springs being used as the controlling force.

The insulation is the most important feature in an instrument of this type intended for high voltages; the use of oil has many advantages which may be summarized as follows:

(1) The distance between the operating elements is lessened, and the actuating forces are greatly increased, due not only to the smaller

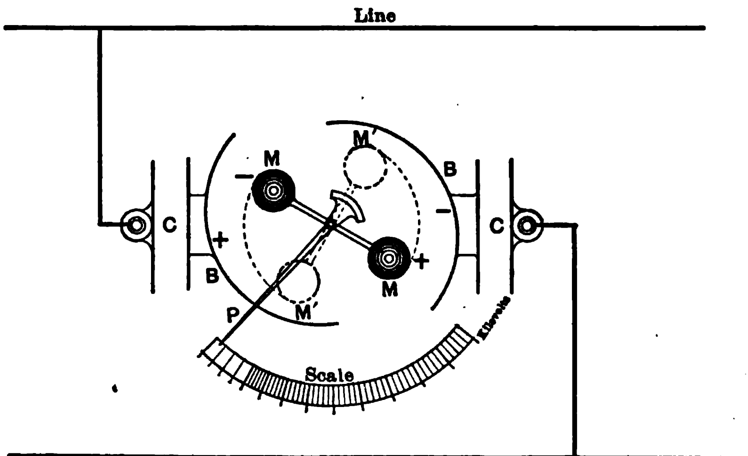

FIG. 48. Mechanism of the Westinghouse static voltmeter for extra high voltages.

distance between the parts, but also to the increased specific inductive capacity of oil over air.

(2) Oil acts as a dampener and makes the instrument nearly "deadbeat."

(3) The oil buoys up the moving element, practically removing all weight from the bearings. This does away with friction and makes the instrument much more accurate.

44. Summary of the Above Described Types of Instruments. — Soft-iron instruments are the least expensive and the least accurate; they are mostly used for switchboard work. Thomson ammeters (Fig. 32), though in this class, are quite accurate for alternating-current measurements. For accurate direct-current measurements, moving-coil instruments are used exclusively. For accurate alternating-current work dynamometer type and hot-wire instruments are used to a considerable extent. Portable induction-type instruments are very convenient, and are sufficiently accurate for many practical

purposes. Electrostatic voltmeters are used mostly in high-tension work and in special research.

45. Requirements for Good Ammeters and Voltmeters. — The principal requirements for a good measuring instrument are:

(1) Permanency of calibration;

(2) Insensibility to stray magnetic fields;

(3) "Dead-beat" quality, *i.e.*, the instrument should not swing too long before giving a definite indication;

(4) Suitable character of the scale.

All these requirements are met to a larger or smaller degree in modern ammeters and voltmeters. However, the more strict the requirements, the more expensive becomes the instrument; it is therefore advisable not to demand greater accuracy than a specific case may require. The following remarks refer to the foregoing requirements:

(1) *The calibration* may be affected by a change of form or relative position of parts inside of the instrument; by an increased friction in pivots; by ageing of springs or of iron; by permanent magnets losing part of their magnetism.

(2) Some of the above-described types of instruments are inherently less affected by *external stray fields* than others, and all of them can be sufficiently protected by being inclosed in a cast-iron case. Hot-wire instruments are practically unaffected by stray fields, since their action is not based on a magnetic effect; induction instruments are affected very little, since their air gap is small and their own field quite strong. Electro-magnetic instruments are affected the most, and should never be placed near dynamos, or on a switchboard within a loop of bus bars and cables carrying strong currents. Electro-dynamometer type instruments are affected by terrestrial magnetism when used on direct current; therefore in accurate measurements it is essential to reverse the current in the instrument and to take the average of two readings.

(3) *The "dead-beat" quality* is always desirable in an instrument, though usually it can be attained only by the addition of an extra damping device. An aluminum vane is quite frequently used for this purpose, the damping being attained either by the resistance of the air to the movement of the vane, or by placing the vane between the poles of a permanent magnet, so as to induce in it eddy currents. Moving-coil instruments are easily made "dead-beat" by making the frame of the moving coil of aluminum. Eddy currents induced in it by the permanent magnet are sufficient to make the instrument dead-beat (the word "aperiodic" is sometimes used instead of the expression "dead-beat").

(4) Different types of instruments have a somewhat *different character of scale.* The scale of moving-coil instruments is usually perfectly regular, all divisions from zero to full scale being equal (Fig. 33). On the other hand, hot-wire instruments have rather an irregular scale, divisions being crowded on the lower part of the scale (Fig. 41), so that the instrument can be read with fair accuracy at not less than 40 per cent of its full range. Sometimes the scale is made suppressed on purpose in its lower part so as to have larger divisions in the useful range of the instrument. In instruments based on the hot-wire or dynamometer principle, the scale is, of necessity, irregular, since the deflecting force is proportional to the square of the current. *A regular scale is by no means always desirable in switchboard service,* though it is very convenient in testing and for experimental purposes, since it increases the useful range of the instrument.

46. EXPERIMENT 2-A. — Study of Ammeters. — The purpose of the experiment is to learn the construction, good qualities and limitations of the principal types of instruments described in §§ 36 to 43. This should help the student to handle instruments properly in his future work, and to select intelligently the right instruments for a given purpose. The instrument to be investigated must be connected into a circuit; if necessary another instrument, used as a standard, must be also connected into the same circuit, in order to observe the comparative behavior of the two. There are many points in regard to which two instruments of the same range and of different type may be compared to each other; the following are among the most important:

(1) Are there any defects in the construction, such that the instrument cannot possibly have a permanent calibration?

(2) Is the instrument "dead-beat," and if not, how can it be made dead-beat in the most convenient way? The degree of being "dead-beat" can be measured by suddenly closing the circuit on a current that gives a certain per cent of full scale deflection, say 60 or 70 per cent, and by observing the time which it takes for the pointer to become steady at this point. This method of defining the "dead-beat" degree is entirely arbitrary, but if the same procedure is used on *all* the instruments under test, the results are comparable among themselves.

(3) If the instrument is absolutely dead-beat (aperiodic) note how long it takes the pointer to assume its final deflection. Also see to what degree the moving part is capable of following rapid fluctuations of current. This point is particularly important in hot-wire instruments; they are somewhat sluggish on fluctuating loads, because it takes a certain length of time for a wire to change its temperature. Charac-

terize this sluggishness numerically, by varying the current up and down at a certain speed and by a certain percentage; observe the behavior of the instrument under test, as compared to that of the standard instrument.

(4) See if the pointer always returns to zero, or at least to the same point, when the circuit is opened; if not, investigate the cause. In hot-wire instruments a special screw, accessible from the outside, is provided for setting the pointer at zero; it is denoted by S in Fig. 41.

(5) Can the instrument be used indifferently in a vertical and horizontal position? Is the moving part sufficiently well balanced so that small differences in the position of the instrument do not affect the calibration?

(6) What kind of force is used to deflect the pointer from zero position, and what is the resisting force?

(7) How explain the character of the scale (regular, crowded on one side, etc.) by the character of the moving and resisting forces? What changes should be made in the instrument to get a scale more regular, or still more suppressed on one side?

(8) Is the instrument conspicuously bulky and heavy, as a result of a particular construction adopted? What are the principal materials used, and what, in your opinion, are the most important and expensive operations in manufacturing the instrument?

(9) Is the calibration affected by the temperature, and if so, how much? Is there in the instrument any compensation for the influence of temperature? Some alternating-current voltmeters have a small thermometer on the face of the instrument, and an adjustable rheostat in series with the multiplier. In some hot-wire instruments the plate on which the wire is stretched is made of a material having the same expansion coefficient as the wire itself; in this way no stresses are produced in the wire by changes in temperature of the surrounding air.

(10) If the instrument has a shunt, determine if the same has a negligible temperature coefficient, in other words, if the calibration of the instrument changes because of the heating of the shunt.

(11) Determine in how far the instrument is affected by stray magnetic fields and a proximity of large iron masses. Does the iron case of the instrument shield it entirely from these influences, and does it not introduce an error by itself?

(12) Is the instrument influenced by terrestrial magnetism? Is there any means for eliminating this influence, for instance, by reversing the current and taking an average of the two readings? Is there

any position of the instrument with respect to the meridian, such that the above influence becomes a minimum?

(13) Does the instrument show an appreciable hysteresis effect, so that indications on increasing and decreasing currents are different?

(14) Is the calibration the same on D. C. as on A. C., and if not, what is per cent difference and the cause of the difference?

(15) Is the calibration affected by the wave-form of alternating current?

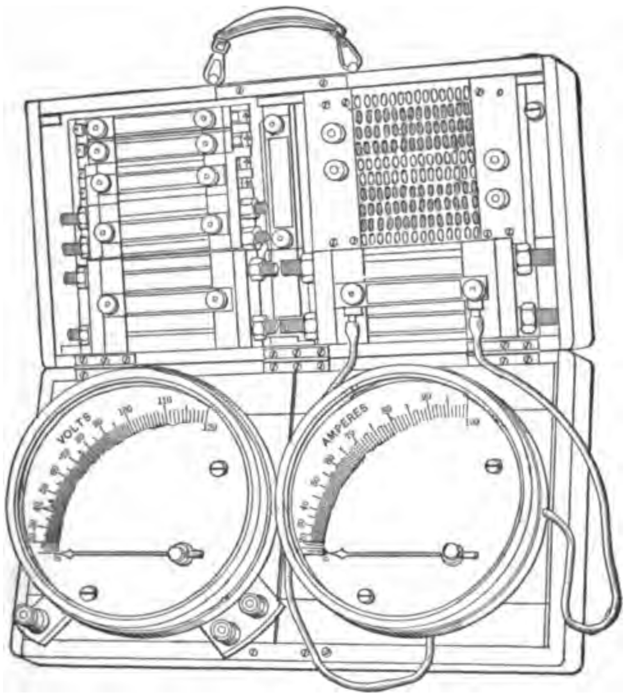

FIG. 49. A portable volt-ammeter with several ranges.

(16) What is the energy consumption in the instrument itself, and how does it compare with that of other instruments having the same range?

Report. Describe the general arrangement of the test, the construction of the instruments used, and give the calibration curves. Also answer for each instrument studied the above 16 questions. Do not repeat the questions; simply refer to them by number.

47. EXPERIMENT 2-B. — Study of Voltmeters. — The experiment is performed in the same way as experiment 2-A.

48. Combination Volt-Ammeters. — It is convenient in some cases to have a portable combination volt-ammeter (Fig. 49) for all-round

testing purposes, or as a secondary standard. The ammeter in the set shown in the sketch is provided with six different shunts covering the range from 25 to 1000 amperes; the voltmeter is provided with two multipliers by means of which its original range can be increased two or four times. Of course, it is not necessary to have the same range in all cases; the shunts and the multipliers must be selected so that the set would cover as much as possible the total range of the work for which it is intended to be used.

49. Polyphase Boards.—In many practical cases, especially in

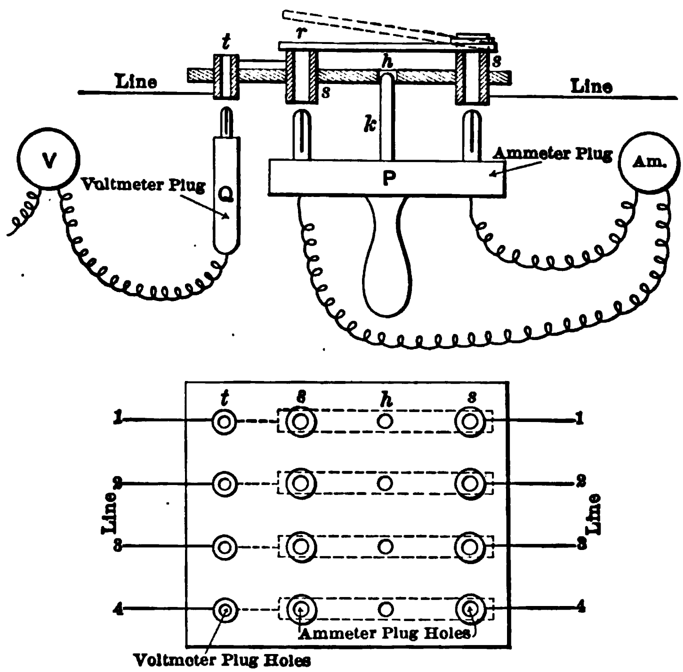

Fig. 50. A plugging arrangement for using one ammeter, one voltmeter, and one wattmeter in several circuits, without interrupting the main current.

polyphase work, it is necessary to measure currents and voltages in more than one part of the circuit. At the same time it is not always possible or convenient to have a sufficient number of ammeters and voltmeters. In such cases so-called polyphase boards may be used, by means of which one ammeter and one voltmeter may be connected in succession to several independent circuits or parts of a circuit. The polyphase boards described below may be used with any number of circuits up to four.

(*a*) *Plug-type board.* The polyphase board shown in Fig. 50 is

very convenient for laboratory purposes. The line wires, in which it is desired to measure currents, are connected to the terminals *t* and *s* of the board. When the plug *P* is out, the circuit of each wire is closed from *t* to the left socket *s* and through the spring *r* to the right socket *s*. If it is desired to measure current, say in line 1, the plug *P* is inserted in the corresponding receptacles *ss* as far as it will go. The pin *p* enters the hole *h* and opens the spring contact *r*, as shown by the dotted lines. But before the circuit is opened at *r*, it is shunted between the receptacles *ss* through the ammeter *Am*. When the plug is taken out, the spring closes the circuit at *r* before the ammeter circuit is opened. In this way the line circuit is never completely opened, and there is no sparking at *r* or fluctuation of the load.

The receptacles *t* are intended for two voltmeter plugs *Q*. By inserting these plugs in any two receptacles, the voltage may be meas-

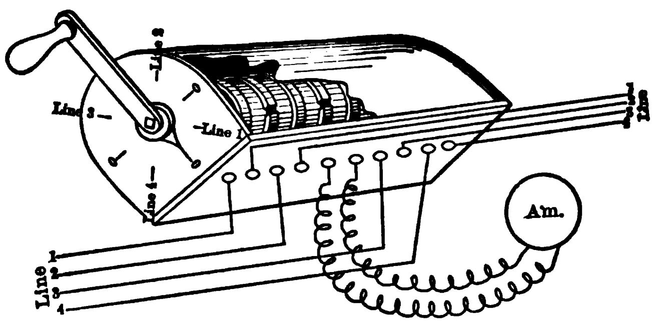

FIG. 51. A controller for connecting an ammeter and a wattmeter into several lines in succession, without opening the main circuit.

ured between any two lines or phases. The same polyphase board accommodates, if necessary, a wattmeter. The current winding of the wattmeter is connected in series with the ammeter, the potential winding in parallel with the voltmeter. Inserting the plugs *P* and *Q* automatically connects the ammeter, the voltmeter and the wattmeter in the desired phases.

(*b*) *Controller-type board.* Another convenient device for the same purpose is shown in Fig. 51. It is intended for transferring the ammeter only from one circuit to another. A separate switch must be used for transferring the voltmeter, as with the polyphase boards shown in Figs. 52 and 53. The device is an ordinary drum-type controller; the lines and the ammeter leads are connected to stationary fingers. The revolving drum is provided with copper contacts which establish the required connections between any of the lines and the ammeter.

When the pointer on the handle shows "line 1," the ammeter measures the current in this line; when the handle is in one of the "O" positions, all the lines are connected direct, and the ammeter is out

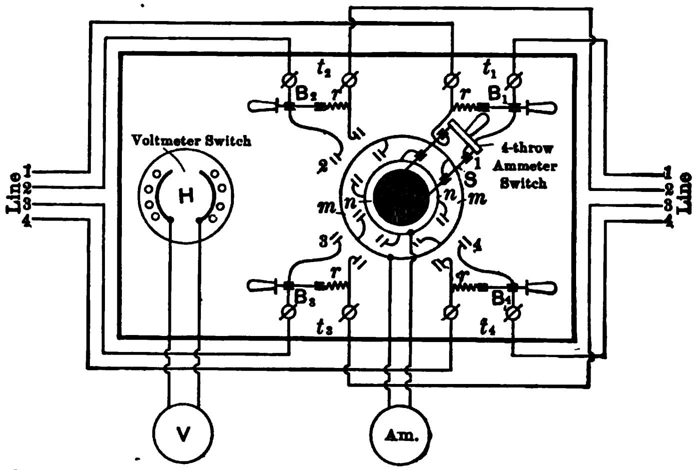

FIG. 52. A polyphase board with one multi-throw switch for currents.

of the circuit. This type of polyphase board is very convenient to handle, especially when readings must be taken in rapid succession.

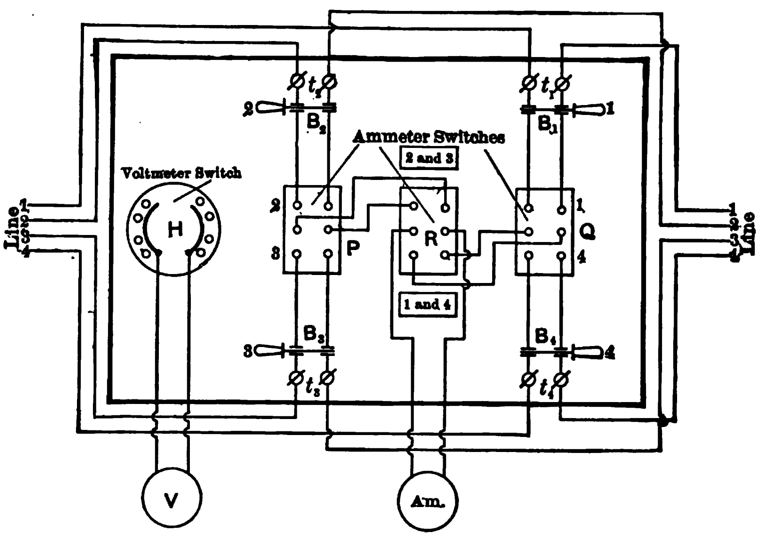

FIG. 53. A polyphase board with three double-pole double-throw switches for currents.

(c) *Boards with knife-switches.* The boards shown in Figs. 52 and 53 are not so convenient in operation as the two devices described

above, but they can be built with less difficulty, by using ordinary knife-switches. The ammeter and the voltmeter switches are entirely separate. The lines are connected to four pairs of terminals t_1, t_2, t_3 and t_4. When the switches B_1, B_2, B_3 and B_4 are closed, the currents flow directly through the lines, outside the ammeter. To read amperes in phase 1, throw the central radial switch S (Fig. 52) in position 1, and open the switch B_1. The current from the left terminal t_1 flows through the left blade of S, connection n, ammeter Am, connection m and the right blade S to the right terminal t, and to the line. Resistances r in series with the switches B are intended to compensate for the resistance of the ammeter and the leads, so that the total resistance of the line remains the same, whether the switch B is open or closed.

The polyphase board shown in Fig. 53 differs from that of Fig. 52 in that the connections are accomplished in it by three ordinary double-pole double-throw switches P, Q and R, instead of by a special radial switch S.

50. Recording (Graphic) Instruments. — It is often of importance to have a continuous record of the performance of electrical machinery, partly as data for economic and engineering calculations, partly as a check on station attendants. Recording ammeters, voltmeters, wattmeters, etc., are used for this purpose. The record is traced automatically on a strip of coördinate paper by a pen fastened to the end of the pointer of the instrument. The paper is moved at a constant speed by a clock mechanism. Any of the indicating instruments described in §§ 36 to 43 may be adapted to be used as a recording instrument. Fig. 54 shows a Bristol recording ammeter based on the electro-magnetic principle. A is the stationary coil through which the current to be recorded flows. The magnetic field produced by the coil attracts the soft iron disk B which rests on knife-edge supports C and D. The supports have a lateral spring action, which opposes the movement of the disk. The motion of the disk B is transmitted

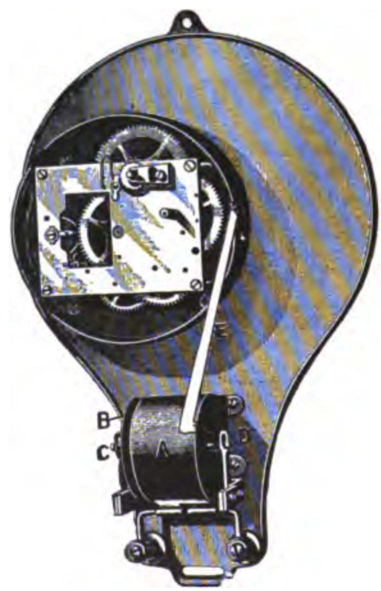

FIG. 54. The Bristol recording ammeter.

to the recording pen-arm E, which traces a record on a sheet of paper, as shown in Fig. 55. The paper is driven by the clock mechanism shown in the upper part of the instrument. One revolution of the paper may be had in 24, 6 or even 1 hour, as desired.

Fig. 56 represents a recording ammeter based on the moving-coil principle; the ammeter movement proper is in the upper part, the

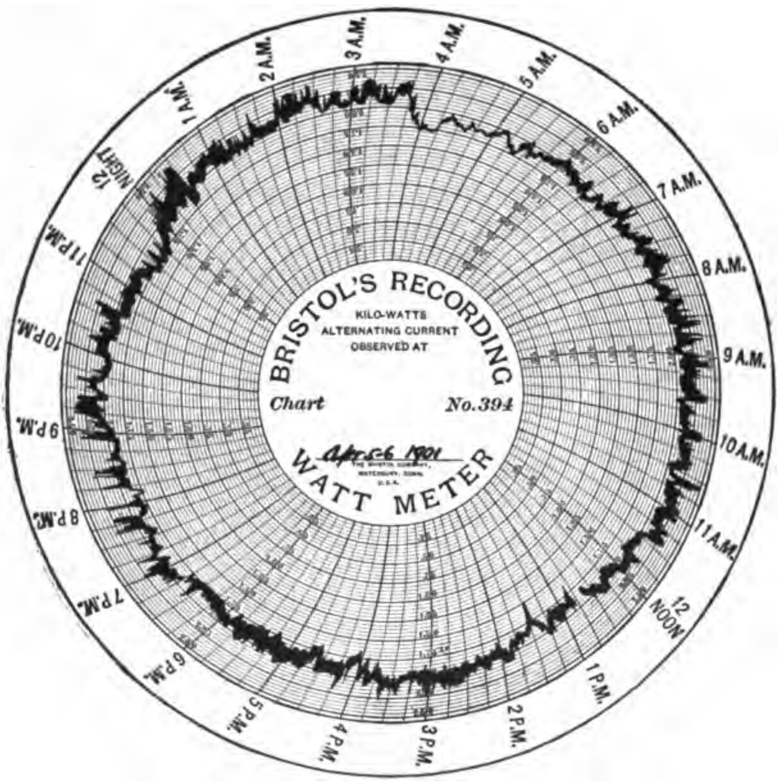

FIG. 55. A 24-hour record taken on a fluctuating load.

recording drum and the clock are underneath. A shunt connected into the main line is shown below the instrument. There are similar instruments on the market, based on the hot-wire and on the electro-dynamometer principles.

The imperfections common to the above recording meters are:

(1) The friction between the pen and the paper impairs the accuracy of the record; or else it necessitates making instruments with a high torque, consequently with a considerable power consumption.

(2) The clock must be periodically wound up.

(3) The records are made either on a circular sheet (Fig. 55) which has to be replaced each day, or on a roll of paper with curved coördinates (Fig. 56); in either case the records are in a form inconvenient for calculations or for the use of a planimeter.

These objections are eliminated in recording meters operating on the "relay" principle and described in the next paragraph. The improvement is, however, obtained at a considerably increased cost and complication of the instrument.

FIG. 56. A recording ammeter with a moving-coil mechanism.

51. Recording Meters Operating on the Relay Principle. — The three above-enumerated objections are eliminated in the following way in meters operated on the relay principle:

(1) The movement proper of the meter operates merely a set of contacts (Fig. 57) which close an auxiliary circuit. This circuit energizes the solenoids which operate the pen; a comparatively large amount of energy is not objectionable in this case, nor does pen friction at all impair the accuracy and sensitiveness of the instrument.

(2) The clock mechanism which moves the paper is made electrically self-winding, say once an hour, and does not require any attention.

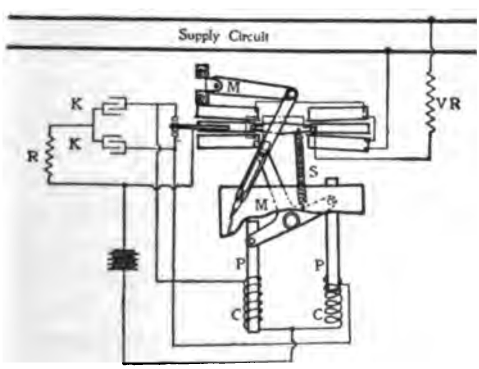

FIG. 57. A diagram of the Westinghouse recording voltmeter, showing the relay principle.

(3) The recording pen is made to move across the paper in a straight line, and the record is obtained on a continuous sheet of paper ruled with rectangular coördinates.

A complete set of recording instruments embodying these features are built by the Westinghouse Electric and Manufacturing Company. The ammeters, voltmeters and wattmeters operate on the dynamometer principle used in the Kelvin

balance (Fig. 74); frequency meters, power factor meters, etc., are built with the same movement as in the corresponding indicating instruments (Figs. 425 and 85).

A recording voltmeter of this type is illustrated in Fig. 58; the details of connections are shown in Fig. 57. The instrument has four stationary coils and two movable coils between them, arranged exactly as in the Kelvin balance. The movable part is provided on the left side with a contact arm which closes one or the other of the two contacts between which it swings. The auxiliary D. C. source is represented schematically by a battery; the two solenoids CC which operate the pen are connected in parallel, and each is connected to one of the above mentioned contacts. The condensers KK and the resistance R are for the purpose of eliminating sparking at the contacts. The leverage MM of the pen is connected by the spiral spring S to the movable part of the voltmeter.

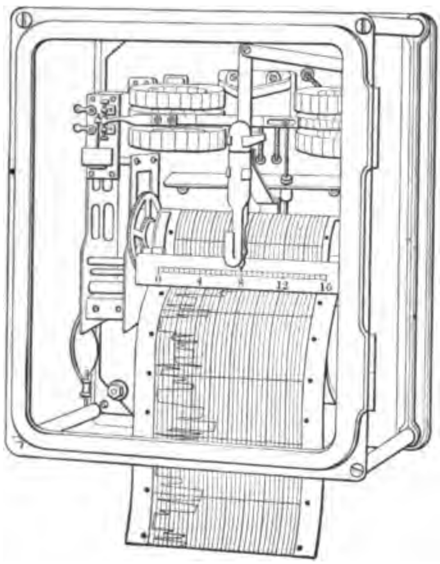

FIG. 58. The Westinghouse graphic recording voltmeter.

The six coils constituting the voltmeter itself are all connected in series across the circuit in which is desired to record the voltage; VR is the multiplier. Suppose that the position of the pen at a certain moment corresponds exactly to the voltage of the line, and both contacts are opened. If the line voltage drops, the spring S overcomes the attraction between the movable and the stationary coils and closes the upper contact. A current flows from the battery into the left solenoid C, a pull is exerted on the plunger P, and the pen begins to move to the left tracing a record. The movement of the pen reduces the tension of the spring S; when the pen arrives at the right point, the electro-magnetic pull between the stationary and the moving coils of the voltmeter becomes just sufficient to overcome the tension of the

spring, and the contact is broken. The pen remains in this position until a new change in voltage occurs.

In reality the pen follows variations in voltage almost instantaneously. The pen (Fig. 58) is made of glass and is provided with a reservoir of a sufficient size to hold ink for a continuous record of two months. The quickness of motion of the pen is regulated by two dash-pots connected to the moving coils. The sensitiveness of the record may also be varied by adjusting the distance between the contacts. The rate of feed of paper may be varied within certain limits.

52. Recording Ammeters for Rapidly Fluctuating Loads. — The above-described recording instruments are not suitable for accurately recording rapidly fluctuating currents, such, for instance, as are taken by street cars during periods of starting and accelerating (Fig. 515). Instruments are required in this case which possess a powerful torque combined with a high rate of paper feed; in addition the instrument must be able to stand the vibrations of an electric car. An ammeter of this kind has been built and successfully applied to car tests by the General Electric Company. A description of the instrument may be found in an article by Mr. A. H. Armstrong, in the *Transactions of the A. I. E. E.*, Vol. XXII, p. 689. Another arrangement with which any ordinary ammeter may be used is shown in Fig. 514. The device is non-automatic; the observer has to follow the ammeter pointer with a handle which traces the record.*

53. EXPERIMENT 2-C. —Study of Recording Instruments. — Different types of recording instruments are described in §§ 50 to 52. The points to be investigated are:

(1) Construction of the indicating and of the recording parts.

(2) Promptness of response to sudden fluctuations.

(3) Pen friction and its influence on the sensitiveness of the instrument.

(4) Character of the scale of the record.

Report. State your findings and explain how you would figure out the average current or the average voltage, if the record has curved coördinates as in Fig. 55.

* See also Ashe and Keiley, *Electric Railways*, pp. 48 and 50.

CHAPTER III.

AMMETERS AND VOLTMETERS — CALIBRATION.

54. Primary and Secondary Standards. — The absolute values of the ampere, volt and ohm are established by an international agreement, and primary standards of these quantities are maintained by the respective governments — in this country by the Bureau of Standards of the Department of Commerce and Labor. Whatever the theoretical reasons are for the selection of certain values as units, for practical purposes they are as arbitrary as the standard inch or the pound. The industry merely demands that the units be of a convenient size and easily reproducible with a sufficient accuracy.

It is not necessary to have primary standards of all the three quantities — the volt, the ampere and the ohm. According to Ohm's law, when two of these are known, the third is represented by their product or ratio. The unit of resistance, or the international ohm, is officially defined as being represented by the resistance of a column of mercury of a certain length and mass, and at a specified temperature. The international ampere is defined as the current which deposits in one second of time a specified quantity of silver out of a solution of nitrate of silver, under certain definite conditions. As a consequence, the international volt is the e.m.f. which, being applied at the terminals of a standard ohm, produces in it a current equal to one ampere (for details regarding these units see any electrical pocket-book).

The mercury ohm and the electro-chemical ampere are standards hardly suitable for practical purposes. Secondary standards are therefore used in practice, calibrated to these. The most popular secondary standards are: Resistances made of wire or strip, and standard cells for producing known e.m.f.'s. Current is determined either as the ratio of volts to ohms, or standard ampere balances are used (§ 72).

The calibration of ammeters and voltmeters with a standard cell requires rather delicate and complicated arrangements and allows of an accuracy not needed for many practical purposes. In places where many instruments must be calibrated in a comparatively short time, and extreme accuracy is not required, it is customary to use good ammeters and voltmeters as intermediate standards; they are

checked from time to time with the primary standards kept in the laboratory. We shall first describe simple calibrations by means of intermediate standards, and then give the methods for checking the standard instruments themselves.

55. Calibration of D. C. Ammeters with a Standard Milli-Voltmeter and a Shunt. — Standard D. C. instruments are invariably of the moving-coil type, because of the accuracy and sensitiveness of this construction. As was explained in § 38 ammeters based on this principle

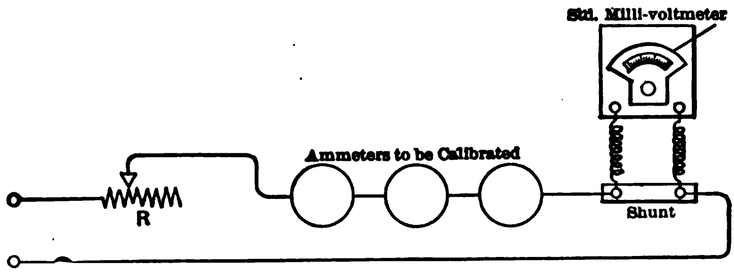

FIG. 59. Calibration of ammeters with a standard shunt and a standard milli-voltmeter.

are in reality milli-voltmeters which measure voltage drop across a shunt (Fig. 35). Therefore, a standard milli-voltmeter and a set of standardized shunts covering the required range of currents is all that is necessary for calibrating D. C. ammeters (Fig. 59). The ammeters to be calibrated are connected to a steady source of direct current in series with a standard shunt and the regulating resistance *R*. A standard milli-voltmeter is connected across the terminals of the shunt. The current is adjusted to a desired value, and the ammeters and the milli-voltmeter are read simultaneously; the current is changed, new readings taken, etc.

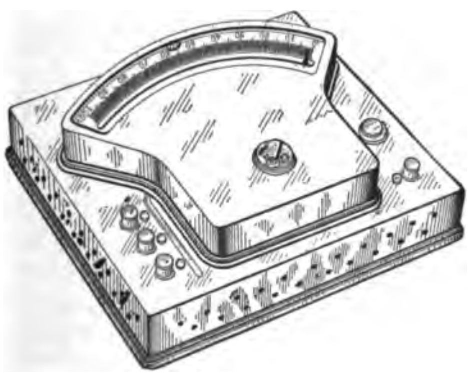

FIG. 60. The Weston standard semi-portable voltmeter (or milli-voltmeter).

A standard milli-voltmeter for accurate calibration is shown in Fig. 60; it is similar to ordinary portable instruments, but is several times

larger and has a scale shown in Fig. 61. With this scale parts of divisions may be read much more accurately than with an ordinary scale, such, for instance, as in Fig. 33. The calibration of the instrument depends to a slight degree upon its temperature; a thermometer is provided on the base of the instrument so that the necessary correction

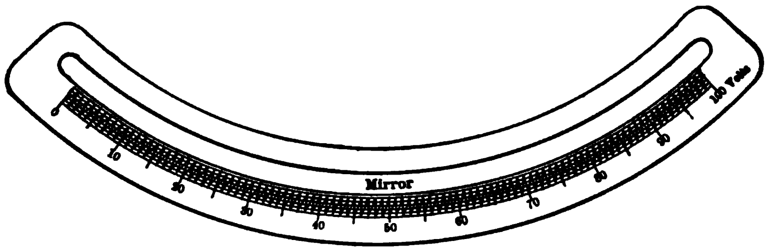

FIG. 61. The precision scale used in Weston standard instruments.

may be taken into account. The scale is provided with a mirror (Fig. 61); in taking readings the observer's eye must be in such a position that the end of the pointer is seen to cover its image in the mirror.

The results of the calibration are given either in the form of a table, or a curve is plotted giving true amperes to actual readings as abscissæ. Some prefer to plot calibration curves in the form shown in Fig. 62,

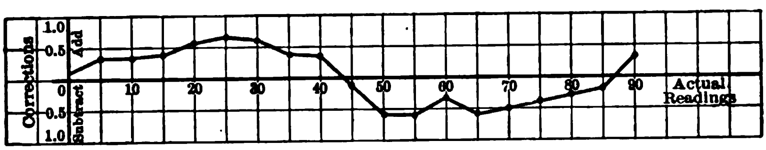

FIG. 62. Calibration curve of an instrument.

instead of true readings, corrections only are given, in scale divisions or in per cent.

If a wide range of amperes is to be covered, one shunt is not sufficient. Suppose, for instance, that the milli-voltmeter gives a full scale deflection with a current of 1000 amperes flowing through the shunt. With 100 amperes the deflection will be only 10 per cent of the scale; it is hardly advisable to go below this, as the accuracy of the readings is impaired. Thus below 100 amperes another shunt of ten times the resistance is required; it will give a full scale deflection at 100 amperes and may be used down to 10 amperes. The next shunt will serve from 10 to 1 amperes, etc.

Not only ammeters, but milli-voltmeters and shunts may be calibrated in a similar way. To calibrate a shunt, connect it in series with a standard shunt (Fig. 59) and measure the voltage drop with

a calibrated milli-voltmeter, first across the standard shunt, and then across the shunt to be calibrated. If the line current is constant, the ratio of readings will give the ratio of resistances of the two shunts. An ammeter should be kept in the circuit to be sure that the current remains unchanged between readings. It is well to use a double-throw switch with mercury contacts when changing the milli-voltmeter from one shunt to the other; ordinary knife-switches have an appreciable contact resistance, which may vitiate the results.

To calibrate a milli-voltmeter it is connected across a shunt in parallel with a standard milli-voltmeter, and simultaneous readings are taken on both instruments.

56. EXPERIMENT 3-A. — Calibrating D. C. Ammeters with a Milli-Voltmeter and a Shunt. — The method is explained in the preceding paragraph. Connect several ammeters as in Fig. 59 and calibrate them throughout their range. Then calibrate a shunt; give its temperature correction, if any. Calibrate a milli-voltmeter; see if the length of the leads and the presence of a switch in the circuit influence the indications.

Report some of the results in the form of curves showing true amperes to actual readings as abscissæ; other results in the form of correction curves, as in Fig. 62.

57. EXPERIMENT 3-B. — Calibrating A. C. Ammeters with Intermediate D. C. — A. C. Standards. — Hot-wire and dynamometer-type ammeters (§§ 40 and 41) may be calibrated with direct current, as in Fig. 59, and used with alternating currents. One precaution necessary when using an electro-dynamometer on direct current is to eliminate the influence of the terrestrial magnetism on the moving coil. This influence is reduced to a minimum by placing the moving coil in a plane perpendicular to the magnetic meridian. It is also well to take readings with the same current flowing through the instrument in both directions and to average the two deflections. Precision dynamometers are made astatic, that is to say, they have two stationary and two moving coils, one system above the other. The direction of the currents is such that the influence of the terrestrial magnetism is cancelled.

Soft-iron and induction-type ammeters (§§ 36 and 42) must be calibrated with currents of the same frequency for which the instrument is intended to be used. If an accurate A. C. standard, such as a Kelvin balance or a precision dynamometer, is not available, the instruments may be calibrated by using intermediate D. C.-A. C. standards (Fig. 63). Hot-wire instruments are particularly well adapted to be used as intermediate standards. The double-pole double-throw switch S is

first thrown to the left, and the hot-wire instrument C is calibrated with the direct current standard instrument A. Then the switch is

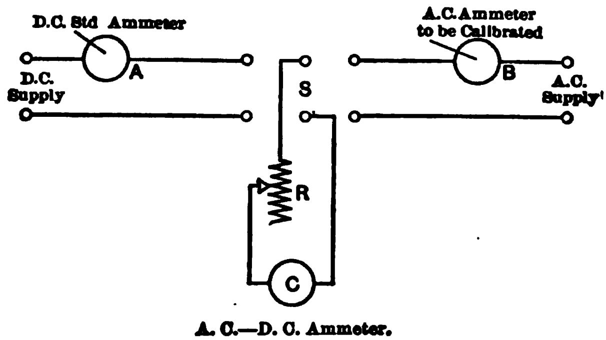

FIG. 63. Calibration of an alternating-current ammeter by means of an intermediate A.C.—D.C. instrument.

thrown to the right and the instrument B is calibrated with C, using alternating current. It is important that the hot-wire instrument

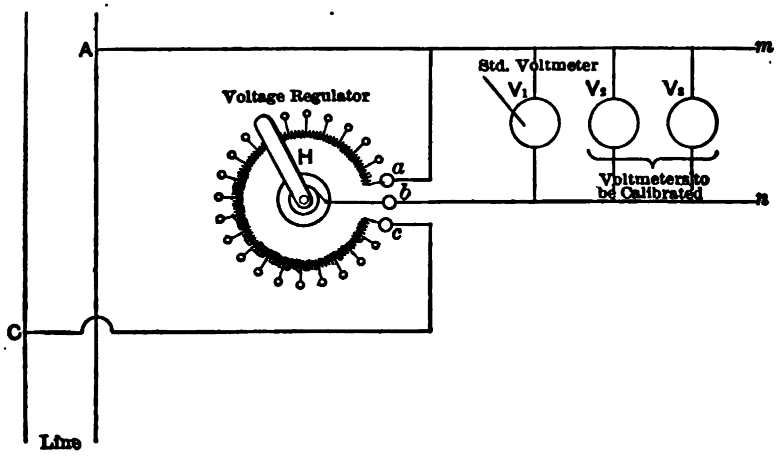

FIG. 64. Calibration of voltmeters.

should preserve its zero during the test; it may be set to zero by the regulating screw S (Fig. 41).

58. EXPERIMENT 3-C. —Calibrating D. C. Voltmeters with a Standard Voltmeter. — The connections are shown in Fig. 64; the voltmeters V_1, V_2, V_3, etc. are connected in parallel between two bus-bars A-m and b-n. The terminals a and c of a high-resistance rheostat are connected across the source of supply; by means of the sliding arm

H connected to *b*, any part of the total line-voltage may be applied at the terminals of the voltmeters. When *H* is in position *a*, the pressure between *m* and *n* is = 0; when *H* is in the position *c*, the total line-voltage is applied between *m* and *n*. One of the voltmeters is a standard instrument with which the others are to be compared. An ordinary embedded-type field rheostat is convenient for use as a voltage regulator. It usually has only two terminals *a* and *b*; it is easy to solder to it a third terminal *c*.

Calibrate the voltmeters with and without multipliers; see if the instruments themselves or the multipliers have an appreciable temperature coefficient. Plot calibration curves as specified in § 56.

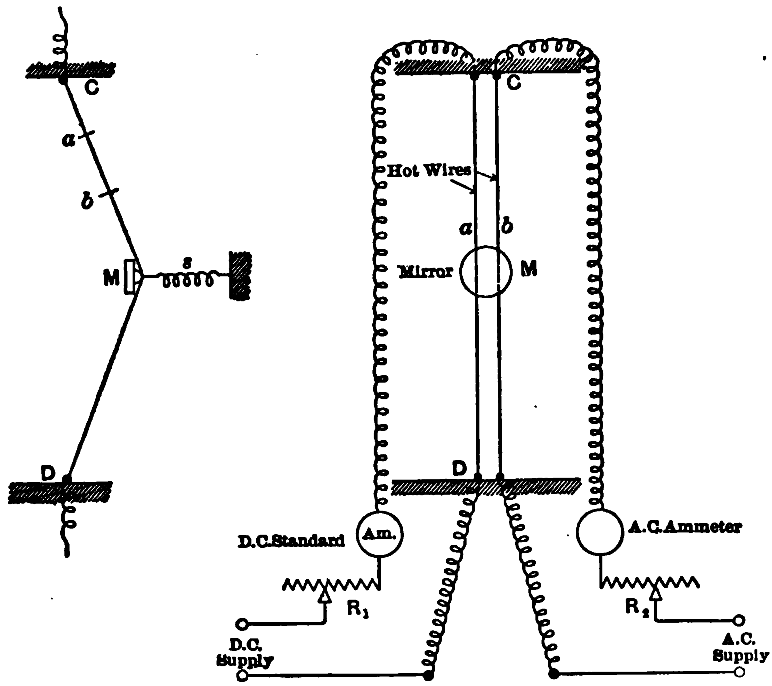

FIG. 65. The Leeds & Northrup comparator, for accurate measurement of alternating currents and voltages.

59. EXPERIMENT 3-D. —Calibrating A. C. Voltmeters with an Intermediate D. C. — A. C. Standard. —The arrangement of the test is similar to that of § 57, except that the instruments to be calibrated are connected in parallel as in Fig. 64.

60. Leeds and Northrup Comparator. — To avoid the necessity of using an intermediate standard, as in Fig. 63, Dr. E. F. Northrup devised an ingenious comparator shown diagrammatically in Fig. 65.

By means of it any A. C. ammeter or voltmeter may be calibrated directly with a D. C. standard. The comparator is essentially a differential hot-wire instrument, which shows zero when the alternating and the direct currents to be compared are equal.

Two identical wires *a* and *b* are stretched between the bases *C* and *D* and have a small mirror *M* fastened to them. A spring *s* pulls the wires backward, and keeps them taut. When a current is sent through one of the wires, that wire is heated and slackens; the spring *s* deflects the mirror, and the deflection is read by means of a telescope and a scale, as with an ordinary galvanometer. If the same current flows simultaneously through both wires, they recede by the same amount, and the mirror continues to show zero.

The actual zero of the instrument is determined by sending a direct current through both wires connected in series. Then an alternating current is sent through the wire to the right and the A. C. ammeter to be calibrated. A direct current is sent through the other wire and the standard ammeter. By regulating the rheostats R_1 and R_2, the values of the currents are adjusted until the mirror comes back to zero. Then the currents flowing through the two ammeters are equal to each other. For the sake of simplicity, total currents are shown flowing through the hot wires. In reality shunts are used on both sides, so that only a small part of total currents passes through the comparator. The same comparator provided with suitable multipliers may be used for calibrating A. C. voltmeters.

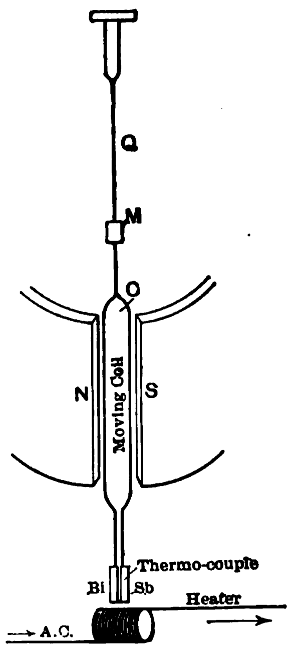

FIG. 66. The Duddell thermo-galvanometer.

61. Duddell Thermo-Galvanometer. — For a long time there has been felt the need of an instrument for measuring small alternating currents with the same accuracy with which small direct currents are measured with moving-coil galvanometers. In § 37 it is explained that moving-coil instruments cannot be used on alternating currents because of the unidirection effect of the permanent magnet. Mr. Duddell ingeniously combined the moving-coil and the hot-wire principles (Fig. 66) and obtained an extremely sensitive A. C.–D. C. instrument with a wide range. The alternating current to be measured is sent through a resistance or the "heater" shown on the bottom. The

heat of the current affects the thermal junction *Bi-Sb* (bismuth-antimony) which produces a direct current in the loop *C*. The same is deflected by the permanent magnet *NS* against the torsion of the quartz fiber *Q*. The sensibility of the instrument depends upon the resistance of the heater and upon its distance from the thermal junction. The instrument can evidently be calibrated with direct current and used with alternating currents. There is no doubt that this thermo-galvanometer will become of importance in measuring high frequency A. C. currents, notably in wireless telegraphy, telephone transmission, X-ray tubes, etc. The instrument is probably suitable for use, in some cases, as an intermediate D. C. to A. C. standard.

62. Standard Cells. — Standard voltmeters and milli-voltmeters used for calibration, as described in §§ 55 and 58, are sufficiently accurate for most practical purposes, provided they are periodically compared to a primary standard of e.m.f. The so-called "standard" cells, which are special primary batteries, are used at present for representing the normal value of the volt.

The standard cell used at present is the Weston cadmium cell; its construction and chemical composition are shown in Fig. 67. There are two forms of cadmium cell, in one of which the cadmium sulphate solution contains solid crystals of cadmium sulphate — this cell is known as the *saturated form*. The other form, in which the solution is saturated at 4 degrees C., is called the *unsaturated form*. It has practically no temperature coefficient. The normal value of the e.m.f. of this cell is 1.01985 volt, at any temperature between 10 degrees C. and 35 degrees C. The saturated form has a slight temperature coefficient; its electromotive force, at any temperature, is given by Jaeger as:

$$1.0186 - 0.000038\ (t - 20\text{ degrees}) - 0.00000065\ (t - 20\text{ degrees})^2$$ volts.

The unsaturated form is not so reliable for extremely accurate scientific research, as the standard form; but it is sufficiently accurate and more convenient for ordinary engineering work. With some skill and experience, a standard cell may be constructed with comparatively simple means at hand. For detailed specifications of materials and for other instructions see a paper by Profs. Carhart and Hulett in the *Transactions of the International Electrical Congress, St. Louis*, 1904, Vol. II, p. 109.

Previous to the introduction of the Weston cadmium cell, the Clark standard cell was universally used. It differs from the Weston cell in that zinc is used instead of cadmium. The e.m.f. of the Clark cell is 1.434 volt at 15 degrees C.; it decreases by 0.00115 volt for each 1 degree C. increase in temperature, between the limits of 10 degrees and

25 degrees. Prof. Carhart improved the Clark cell by saturating the solution of zinc sulphate at 0 degree C. The e.m.f. of the Carhart-Clark cell is 1.440 volt; its temperature coefficient is about half of that of the Clark cell.

A very important precaution should be observed in handling standard cells not to draw any appreciable current from them. The cell

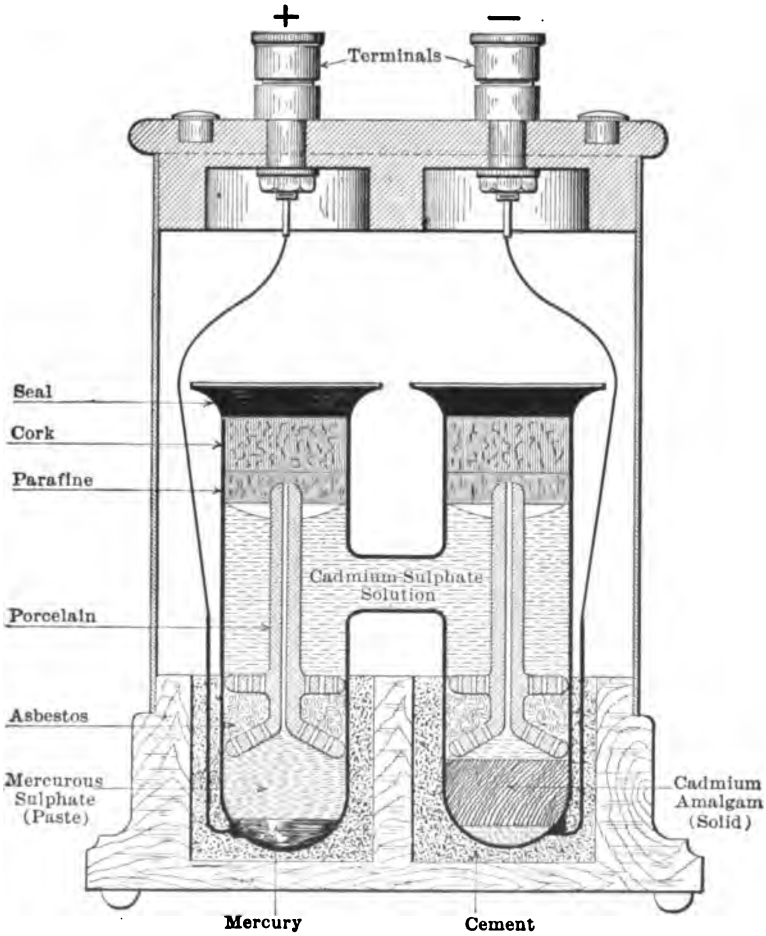

FIG. 67. Cross-section of a Weston standard cell.

becomes polarized almost instantly, and it is doubtful if it ever sufficiently recovers, to be reliable as a standard. The Weston cell should never be closed on a resistance of less than 10,000 ohms, a greater resistance being preferable.

63. Principle of the Potentiometer. — Instruments by means of which voltages are measured in comparison with a standard cell are called *potentiometers* (Figs. 68 and 69). They are used for very accurate measurements of currents, voltages and resistances and for calibration of the corresponding instruments. With a potentiometer,

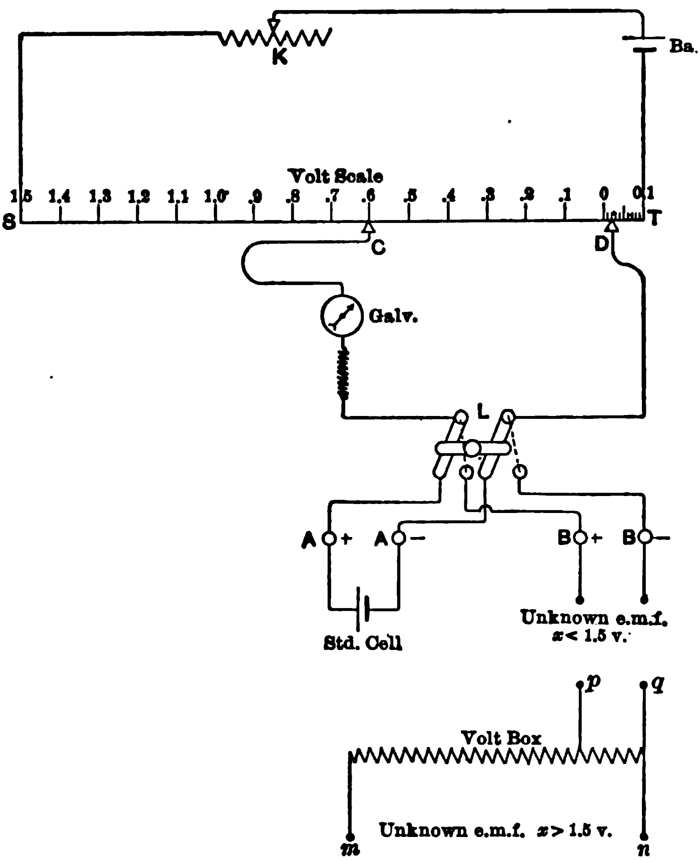

FIG. 68. The potentiometer principle of comparing voltages.

voltages from a fraction of a millivolt to several thousand volts can be accurately compared to the e.m.f. of a standard cell, and currents measured from a small fraction of an ampere to many thousand amperes.

The ordinary potentiometer connections are shown in Fig. 68; for

a clear understanding of the principle involved the student should keep in mind two points:

(a) The standard cell balances the unknown voltage, but is not used as a source of current.

(b) The "zero" method is used so that it is not necessary to know the galvanometer constant.

A slide-wire ST is connected in series with one or two storage cells $Ba.$ and a regulating rheostat K; a constant current is thus established in ST. Any desired voltage drop may be had between the contacts C and D by moving them along the slide-wire, or by regulating the rheostat K. The contact C is for crude regulation, D for fine regulation. The drop between C and D is balanced against the standard cell and against the unknown e.m.f. in succession. A balance is recognized by the galvanometer needle returning to zero. The ratio of the lengths C-D in the two cases is equal to the ratio of the e.m.f.'s under comparison, provided the current in ST remains constant. By means of the double-throw switch L connections are conveniently changed from the standard cell to the unknown e.m.f., and back.

In order to make the arrangement direct-reading, the contacts C and D are set beforehand so as to balance the voltage of the standard cell at the proper divisions of the scale — in case of the Weston cadmium cell about 1.02 volt. (See § 62.) The switch L is thrown to the left, and the rheostat K adjusted until the galvanometer returns to zero. Then the switch is thrown to the right, and the galvanometer balance again obtained by shifting C and D. With the position shown in the sketch, the unknown voltage is 0.620 volt.

The potentiometer scale usually has a range of 1.5 volt so that only voltages below this limit can be directly compared to that of a standard cell. For voltages above 1.5 volt a multiplier, or the so-called "volt-box," is used, shown on the bottom of the sketch. It consists of a high resistance with one or more taps at a known part of it, say 1/10, 1/100, etc. The unknown e.m.f. is connected across the terminals m and n; the terminals p and q are connected to the terminals BB of the potentiometer. Let, for instance, the unknown voltage be about 110 volts and the resistance between p and q be 1/100 of the total resistance of the volt-box. Then the voltage drop across pq is only about 1.1 volt and can be directly compared to the e.m.f. of the standard cell. Multiplying the result by 100 we get the actual unknown voltage.

64. EXPERIMENT 3-E. — Study of a Simple Potentiometer. — Before attempting to use the accurate and delicate potentiometers it is desired that the student make clear to himself the working principle of

the potentiometer, according to the simple diagram shown in Fig. 68. A German-silver wire stretched along a uniform scale may be used as the slide-wire; ordinary voltmeter leads with knife-edge terminals for contacts C and D.

(a) Connect the circuits as shown in Fig. 68 and practice in comparing two e.m.f.'s small enough to be within the range of the slide-wire. It is not necessary to use a standard cell; any dry cell of which the e.m.f. has been previously determined will serve the purpose.

(b) Arrange the connections for measuring amperes by means of a

FIG. 69. The Leeds & Northrup potentiometer.

standard shunt (Fig. 59); use the potentiometer in place of a millivoltmeter.

(c) Compare two resistances by measuring the drop at their terminals (Fig. 2).

(d) Finally improvise a volt-box and make clear to yourself the method of measuring voltages beyond the range of the slide-wire.

65. Leeds and Northrup Potentiometer. — A convenient form of potentiometer for ordinary engineering work is the Leeds and Northrup instrument (Fig. 69). The connections are shown in Fig. 70; the same notations are used as in Fig. 68. The larger portion SO of the slide-wire is replaced by 15 five-ohm resistance coils in series, with their terminals connected to contact buttons. This arrangement permits of having a considerable resistance without increasing the size of the instrument. The dial and the handle corresponding to the contact C are visible in Fig. 69 behind the switches. The part of the

slide-wire between O and T is wound on a marble cylinder and is about 16 feet long, its resistance being exactly 5 ohms. The contact D is mounted inside of an aluminum hood and moves up and down with the hood as it turns on a heavy screw projecting from the center of the marble cylinder. The slide-wire makes 10 turns on the cylinder, so that each turn corresponds to 0.01 volt. It is easy to read on the circular scale at least 1/100 of a turn, so that voltages can be accurately read down to 0.0001 volt or 1/10 millivolt.

For measuring very low voltages a 10 times greater accuracy may be obtained by introducing the shunt 10 : 1 (Fig. 70); this is done by

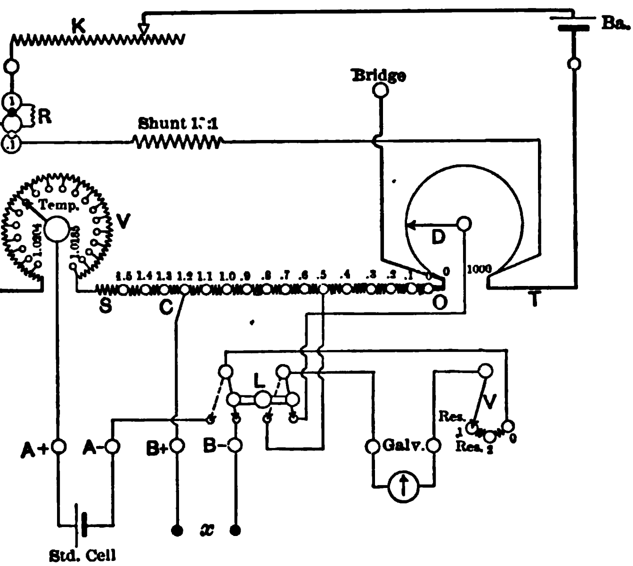

FIG. 70. Diagram of connections of the Leeds & Northrup potentiometer.

changing the plug shown to the left, from the hole 1, to that marked 0.1; the plug and the receptacles are clearly seen in Fig. 69. The resistance of the shunt and that of R bear such a ratio that when the shunt is applied, the voltage drop across the circuit SOT is reduced 10 times, provided the battery current remains the same. This gives the potentiometer a range from 0.15 volt to 0.00001 volt, or 1/100 millivolt. The connections to the standard cell and to the unknown e.m.f. are similar to those shown in Fig. 68. The switch-key V in the galvanometer circuit has three positions; in the two left positions some protective resistance is connected in series with the galvanometer. This is to prevent violent deflections of the galvanometer before the

balance is obtained, and also to protect the standard cell against excessive currents which might polarize it.

The connections are such that the contacts C and D are used for obtaining balance with the unknown e.m.f. only, but not when adjusting the current — this being done by means of the resistance K. It will be seen from the sketch, that the standard cell is connected between the point .5 of the potentiometer resistance and the sliding contact on the dial to the left, marked "Temp." (temperature). The e.m.f. of the Weston cell being about 1.02 volt, the resistances connected to this dial permit the operator to set the potentiometer exactly at the certified e.m.f. of the cell, taking into account small variations depending on temperature or any other causes (§ 62).

By throwing the switch L to the left the balance is obtained by regulating K, *with any position of* C *and* D. This is the distinctive feature of the Leeds and Northrup potentiometer, and has the following advantage: Suppose the resistance K to be adjusted so as to give a balance with the standard cell, the connections being as in Fig. 68. Now the switch L is thrown to the right, and a new balance obtained by moving C and D. In the meanwhile the battery current might have changed; in order to check this, it is necessary to set C and D back into the position corresponding to the e.m.f. of the standard cell, and to throw the switch L to the left. This means setting C and D every time anew, and losing the previous setting; also a loss of time. With the circuits shown in Fig. 70 the setting of C and D may be left intact, and the battery current checked by throwing L to the left and pressing the galvanometer button.

66. Checking Potentiometer Resistances. — Provision is made in the potentiometer shown in Fig. 70 for checking the resistances of the dial and of the slide-wire. The coils in the series SO are each five ohms, and between each there is a brass block with a reamed hole (Fig. 69). A pair of flexible cords, with taper plug terminals to fit the reamed holes, is furnished. These coils can be measured with an ordinary Wheatstone bridge and thus compared with each other to a high degree of accuracy even if the bridge is not accurate. For potentiometer work the essential point is that they should be like each other, not that they should be accurately any particular value. In the same way the resistance of the extended wire can be compared with the resistances of the coils in SO and should be found exactly equal to them. The heavy connector leading out to the binding post marked "Bridge" is provided for this purpose; also that the extended wire may be used by itself as a Kohlrausch bridge (Fig. 16).

The calibration of the extended wire OT on the cylinder may be

checked against the dial resistances *SO* by converting the potentiometer itself into a Wheatstone bridge. To do this, short-circuit the two outside upper binding posts with a heavy copper connector, not smaller than No. 10 B. & S.; also short-circuit the terminals *BB* and throw *L* to the right. Connect the battery between the terminals marked " Ba " and "Bridge." The contacts *C* and *D* form one junction of the two arms on each side of the bridge with the galvanometer between, while the posts " Bridge " and " Ba " form the second junction with the battery between. On one side there are 16 equal resistances of 5 ohms each, the resistance of the temperature dial being supplemented with an extra resistance, so as to make it exactly 5 ohms. If the extended wire be read in its 1000 parts, each of the 16 coils of the potentiometer circuit will be equal to $\frac{1}{16}$ of 1000 or 62.5 divisions when balanced against the wire.

67. Directions for Using Leeds and Northrup Potentiometer. — In view of the popularity of the above-described potentiometer, it was deemed advisable to reprint here the explicit directions for its use, as given by the makers.

Setting up. — All connections must be made as indicated by the stamping on the potentiometer. Particular attention must be given to the polarity of the standard cell, battery and e.m.f., the corresponding + and − signs being marked.

If used with a wall galvanometer having a telescope and scale, it will be found convenient to place the potentiometer so that the telescope is directly over the glass index of the extended wire, thus permitting the observer to read the galvanometer deflections and potentiometer settings without change of position.

Potentiometer current. — A medium-sized storage cell will be found advantageous, producing a steady current. Errors of measurement are frequently made by using an unsteady source of e.m.f.

Setting for standard cell. — Set the standard cell switch to correspond with the certified e.m.f. of the standard cell, as given in its certificate. *Place plug in hole* 1, *and see that it is always in this position when checking against the standard cell.* Place the double-throw switch at Std. Cell. The switch-key should be at the left of the three contacts marked RES., RES. and O, so as to include the greatest extra resistance in series with the galvanometer. This precaution is always to be taken before the final balance is obtained to prevent any violent deflections of the galvanometer.

Adjust the regulating rheostat until the galvanometer shows no deflection. The final galvanometer reading should be taken with the switch-key at zero, so as to remove the series resistance and thus

increase the sensibility. The middle "RES." contact can be used as an intermediate point of contact as the galvanometer balance is approached.

Measurement of unknown e.m.f. — The potentiometer gives direct readings for voltages up to and including 1.6 volt, therefore no voltage exceeding this amount must be connected to the e.m.f. posts of the instrument. For voltages higher than the direct range of the instrument, a volt-box or multiplier must be used.

The standard cell balance having been obtained as described under "Setting for Standard Cell," proceed as follows:

Place the double-throw switch in position E.M.F. and the galvanometer key to the left of the contacts so as to again include the highest series resistance. The balance for the unknown e.m.f. is now obtained by manipulating the tenths switch and rotating the contact on the extended potentiometer wire. The final position of the two contacts in conjunction with the position of the plug at left of instrument indicates the voltage under test as described later.

Plug at 1 *or* .1. — Plug at 1 gives readings for voltage direct from settings of tenths switch and extended wire contact.

Plug at .1 shunts the potentiometer circuit so that the voltage measured is one tenth. Therefore, the readings taken from the settings of the tenths switch and slide-wire contact must be divided by 10.

To balance galvanometer for unknown e.m.f.

> Place plug in hole 1 for voltages up to 1.6.
> Place plug in hole .1 for voltages up to .16.

Rotate the tenths switch (having the galvanometer key at first RES.) until a condition of balance is obtained exactly or approximately. To secure an exact balance, rotate the contact on the extended wire. The unknown e.m.f. can now be read directly from the position of the tenths switch and the extended wire contact if plug is at 1, or by dividing by 10 if plug is at .1.

Example. — A balance was obtained with the tenths switch at 1.3 and the extended wire contact at 176 and the plug at 1. The voltage under test, therefore, is 1.3176. If the plug at .1 had been used the same reading would have indicated .13176.

To ascertain if current in the potentiometer circuit has altered during a measurement, it is only necessary to plug in at 1, place the double-throw switch on Std. Cell and close the galvanometer key. No deflection indicates that current is constant. If previous balance does not exist, the regulating rheostat must again be adjusted until the galvanometer shows no deflection.

68. Nalder Potentiometer. — Another popular potentiometer is that manufactured in England by Nalder Bros. & Co. The instrument

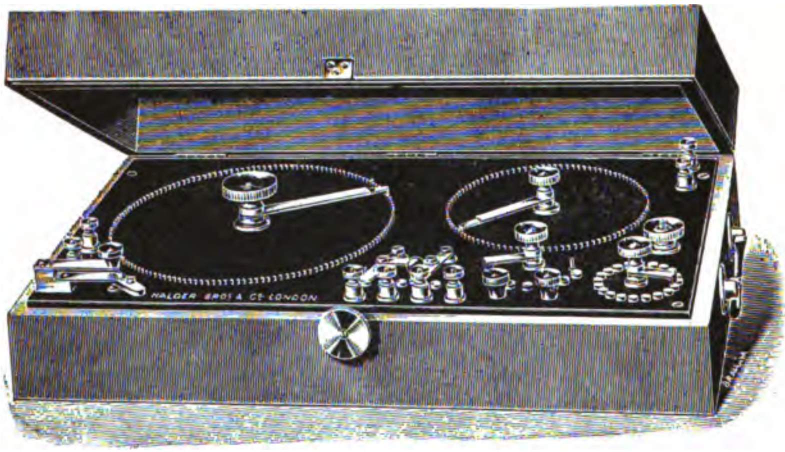

FIG. 71. The Nalder Bros. potentiometer.

is illustrated in Fig. 71; the circuits are shown in Fig. 72. No slide-wire is used, all the resistance consisting of coils of wire connected to contact buttons. The dial to the left corresponds to the part SO of the scale (Fig. 68); the dial to the right is for fine adjustments and corre-

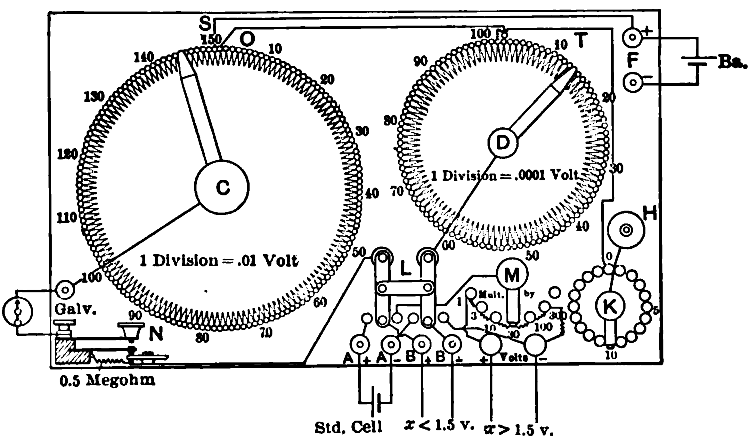

FIG. 72. Diagram of connections in the Nalder potentiometer.

sponds to the part OT. The regulating resistance K is mounted in the case with the rest of the apparatus; it consists of a wire rheostat K for crude adjustment, and of a carbon disk rheostat H for fine regulation.

The multiplier or the volt-box for e.m.f.'s above 1.5 volt is also a part of the instrument itself; the regulating handle of the multiplier is denoted by M. The switch L has three positions, instead of two, as in Figs. 68 and 70; these positions correspond to standard cell, $x < 1.5$ volt, and $x > 1.5$ volt. The galvanometer and the standard cell are protected by a 0.5 megohm resistance; this resistance is in the circuit when the key N is slightly pressed on; by pressing the key as far as it will go, the protective resistance is short-circuited. The circuits are exactly the same as in Fig. 68. The current from the + terminal of the battery flows to S, and through all the coils of the two dials to the regulating rheostat K; thence to H and back to the battery. The potential arm D is connected to the switch L directly — the arm C through the galvanometer and its protective resistance.

To use this potentiometer with a Weston cell set the large dial on 101, the small dial on 98 or 99 according to the certified value of the e.m.f. of the cell (see § 62). Throw L to the left and adjust the current (usually from a large storage cell) by K and H, so that the galvanometer remains on zero when the key N is pressed. Now the potentiometer is ready for measuring e.m.f.'s between the terminals BB or "volts." To measure a voltage above 1.5 volt L is thrown in its extreme right position, and the arm M set at the proper value. The contacts C and D are adjusted until the galvanometer shows zero. With the position of the contacts shown in the sketch, the reading is 1.4514 volts; the multiplier is in position "30," consequently the unknown potential is $1.4514 \times 30 = 43.542$ volts.

If it is desired to determine whether the battery current has changed, the contacts C and D are set back to 101 and 98 (or 99) and the key N pressed. If the galvanometer shows a deflection, an adjustment is made with H, and the unknown voltage measured again. This necessity of destroying the setting of C and D is a drawback of this instrument; it is eliminated in the Leeds and Northrup potentiometer by a somewhat different disposition of the circuits, and by adding the "Temp." dial (Fig. 70).

69. EXPERIMENT 3-F. —Calibrating Voltmeters with a Potentiometer and a Standard Cell. — The theory of the potentiometer is given in § 63; two commercial types are described in §§ 65–68. Study carefully the connections in the potentiometer available; then calibrate with it several voltmeters of different range. Pay particular attention to the sensitiveness and accuracy obtainable and to the factors which influence these. If possible, check the resistances of the potentiometer itself, as explained in § 66; or devise another method more suitable for the apparatus at hand.

70. EXPERIMENT 3-G. —Calibrating Ammeters with a Potentiometer and a Standard Resistance. — The experiment is similar to that described in § 56, except that the voltages across the shunt (Fig. 59) are measured with the potentiometer instead of a milli-voltmeter.

71. EXPERIMENT 3-H.—Comparing Resistances by a Potentiometer. — The method is the same as in Fig. 2, except that a potentiometer is used instead of an ordinary voltmeter or milli-voltmeter. A potentiometer with three pairs of terminals, as shown in Fig. 72, is

FIG. 73. A standard resistance for large currents.

particularly convenient for the purpose. One of the resistances is connected to the terminals *BB*, the other to "volts." If the resistances are very different from each other, it may be necessary to use the volt-box with one of them. It is essential that the current through the resistances under comparison should not change during the test. A standard low resistance is shown in Fig. 73. It has two pairs of terminals, as does an ammeter shunt (Fig. 35). Current is led in through the bent terminals, potential drop is measured between the straight terminals.

72. Ampere Balance. — When using a potentiometer and a standard cell, amperes are measured indirectly as the values of the e.m.f.

and the resistance are found. A direct standard of current is offered by the Kelvin balance (Figs. 74 and 75). It is based on the electromagnetic attraction between stationary and moving coils, and is calibrated either by means of a silver voltameter, or by a potentiometer, with a standard resistance and a cadmium cell.

The instrument consists of four stationary coils *A*, and two movable coils *B* suspended by metal strips *C*, which strips serve also as current leads for the coils *B*. The six coils are connected in series; a current flowing through the coils produces attractions and repulsions, as marked in Fig. 74. The influence of terrestrial magnetism is neutralized, since the current in the two movable coils is flowing in opposite directions.

A weight is placed in the trough *D*; with this weight the movable coils are in balance without current when the sliding weight *w* is in its

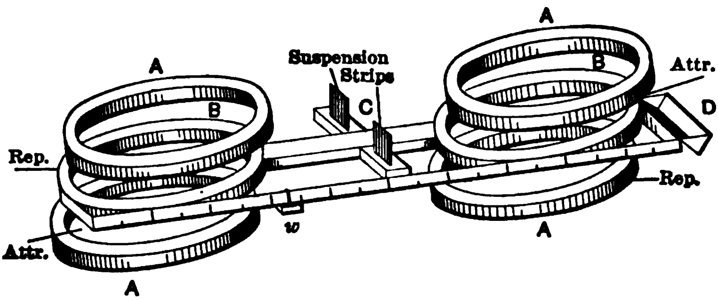

FIG. 74. The principle of the Kelvin balances.

extreme left position; this position corresponds to the zero of the scale. When a current is flowing through the instrument, it is necessary to move *w* to the right in order to keep the movable coils in balance, and current is indicated on the scale by the position of the weight *w*. It will be seen in Fig. 75, that the instrument is provided with two scales: one is the accurate uniform scale; the other, the so-called inspectional scale, is calibrated directly in amperes. The ampere divisions are proportional to the square roots of the distances from the left end of the scale, because the attraction between the coils is proportional to the square root of current (§ 40). The inspectional scale is accurate enough for ordinary purposes; if a greater accuracy is required the uniform scale is used; the current is then calculated by extracting the square root of the reading and multiplying it by the constant of the instrument.

The slipping of the weight *w* into its proper position is performed by means of a self-releasing pendant, hanging from a hook carried by a

sliding platform, which is pulled in the two directions by two silk threads passing through holes to the outside of the glass case (Fig. 75). For the fine adjustment a small flag is provided, as in an ordinary chemical balance. The flag is actuated by a fork having a handle visible below the base. The round knob in the base, fastened to the chain, lifts the moving coils off the suspension, when the instrument is not in use. Four pairs of weights (sliding and counterpoise) are supplied with each instrument; of these the sledge of the moving weights and its counterpoise constitute the first pair. These weights are adjusted in the ratios of 1 : 4 : 16 : 64, so that each pair gives a round number of amperes, or half-amperes, or quarter-amperes, or of decimal subdivisions or multiples of these magnitudes of current, on the inspectional scale.

These instruments can be used equally well with direct or alternating currents, and are made in seven sizes covering the range from 0.01 ampere to 2500 amperes. The smallest size may also be used as a voltmeter, when provided with a suitable high resistance in series (multiplier). Balances are built on the same principle for measuring watts; also composite balances for measuring amperes, volts and watts with one and the same instrument. Detailed instructions for using the balance always accompany the instrument.

73. Absolute Electro-Dynamometer. — The above balances in spite of all their accuracy are but secondary standards, which need to be calibrated with a silver voltameter. There is a continuous effort on the part of physicists to build a satisfactory *primary standard of current* based on the electro-dynamometer principle, the constant of which standard may be deduced theoretically in C. G. S. units *from its geometrical dimensions.* One such "absolute" electro-dynamometer, designed by Pellat, is shown in Fig. 76. It consists of a large stationary coil shown to the left, and a small coil fastened to the beam of a delicate balance. When the instrument is in use the large coil is moved along to inclose the small one. The two coils are connected in series and the electro-magnetic couple of the current is balanced by a weight on the scale pan. The current corresponding to a certain *net* weight on the pan is calculated theoretically from the dimensions of the coils, so that the instrument is a primary standard in the true sense of the word. Standard electro-dynamometers are very expensive; the coils must be finished very accurately, and the whole instrument made of materials which will not change their dimensions with time or temperature.

Three primary standards: (a) standard cell, (b) standard resistance, (c) standard electro-dynamometer, are shown in Fig. 77, con-

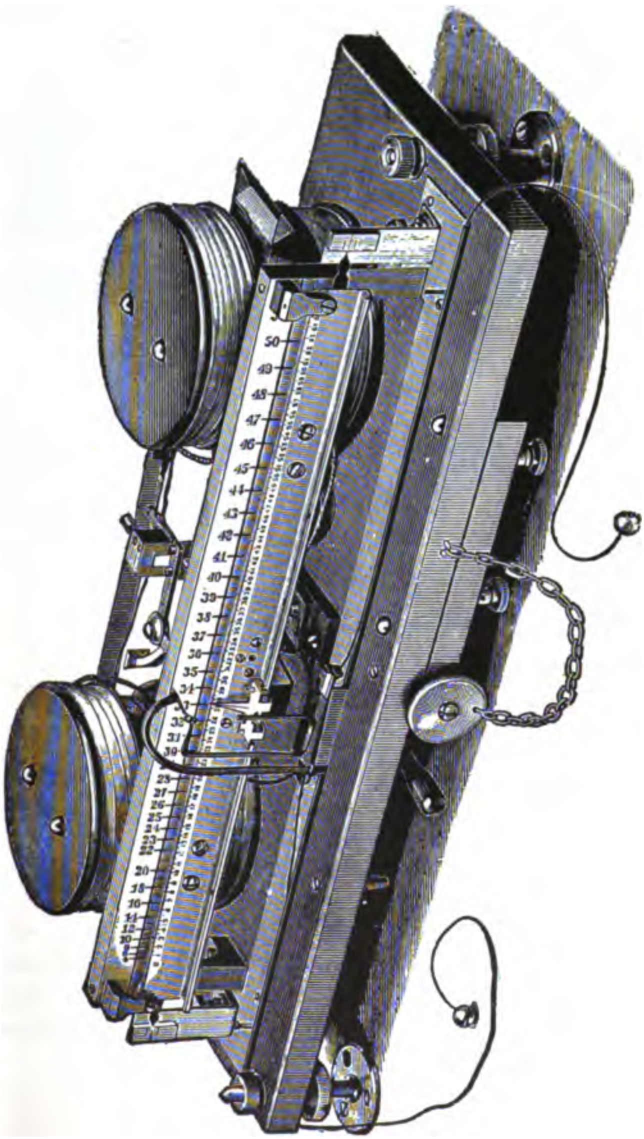

FIG. 75. The Kelvin balance for measuring currents.

nected so that any two of them may be checked by the third. The current is measured by the absolute electro-dynamometer, and also by

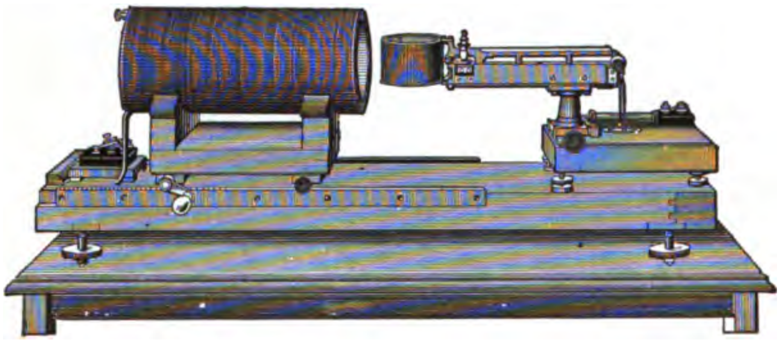

FIG. 76. The Pellat absolute electro-dynamometer.

the standard resistance and the cell. The value of the current is adjusted by the rheostat *R*, so that the galvanometer shows no deflection when the switch *K* is closed. Assuming, for instance, that the electro-dynamometer is correct, and the exact value of the resistance

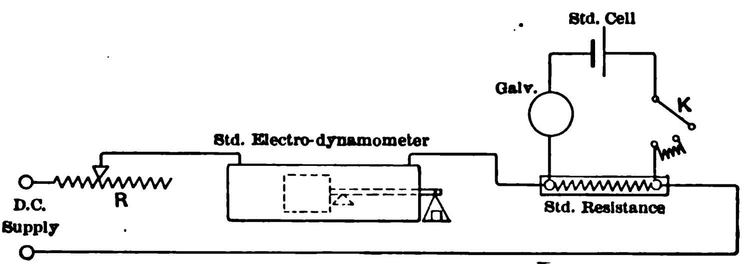

FIG. 77. The mutual check of the three standards; viz., those of current, electromotive force, and resistance.

of the shunt is known, the e.m.f. of the standard cell may be calculated as the product of the current and the resistance. This is the method by which the latest determinations of the e.m.f. of Weston and Clark standard cells were made — see an article by Dr. Guthe in *Bulletin No.* 1 (*Vol.* 2) *of the Bureau of Standards.*

CHAPTER IV.

WATTMETERS AND WATT-HOUR METERS.

74. A WATTMETER is an instrument for measuring electric power developed in a circuit. The name " wattmeter " comes from the name " watt," which is the practical unit of power, in the volt-ampere-ohm system. There are three types of wattmeters: (a) *Indicating wattmeters*, which show instantaneous values of power or the rate at which energy is consumed; (b) *Recording*, or graphic, *wattmeters*, which trace a curve of instantaneous values on a record sheet; (c) *Watt-hour meters*, also sometimes called integrating wattmeters, which show *total energy* delivered during an interval of time.

To make this distinction clearer, take the case of a 100-volt direct-current circuit, in which the current regularly fluctuates between 50 and 70 amperes every 10 seconds. Imagine a wattmeter of each of the three above types connected to such a circuit, and observe their behavior — say for five minutes. The needle of the indicating wattmeter will fluctuate regularly between the divisions of the scale, corresponding to 5000 and 7000 watts. The recording wattmeter will trace a wavy line between the same values (Fig. 55). The dial of the watt-hour meter will show at the end of five minutes

$$\frac{(7000 + 5000)}{2} \times 5 = 30000 \text{ watt-minutes,}$$

or

$$\frac{30000}{60} = 500 \text{ watt-hours.}$$

INDICATING WATTMETERS.

75. Power expended in a direct-current circuit (Fig. 29) is equal to the product of the current delivered times the pressure at which it is supplied; in practical units

$$\text{watts} = \text{amperes} \times \text{volts}$$

or, with the customary notation,

$$w = i \times e \qquad \text{. . . . .} \qquad (1)$$

Thus, in direct-current circuits power may be measured with an ammeter and a voltmeter. In alternating-current circuits, the presence of self-induction and capacity so modifies the relations, that the product "effective volts" times "effective amperes" is not equal to the true average watts expended in the circuit. The relation (1) is, however, always true for instantaneous values of current and voltage; in other words,

$$i.e.\,dt$$

represents the electrical energy delivered to an alternating-current circuit during an infinitesimal element of time dt; i and e are instantaneous values of the current and the voltage. The average energy delivered in one second, or the power in watts,

$$w = \frac{1}{T}\int_0^T i.e.\,dt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where T is the time of one cycle of the alternating current. Assuming that both current and voltage vary according to the sine law, we have

$$i = I \operatorname{Sin} mt$$
$$e = E \operatorname{Sin} (mt \pm \phi)$$

where ϕ is the phase angle by which the e.m.f. leads or lags behind the current, and $m = 2\pi/T$ (see Fig. 102). Substituting in (2) we obtain

$$w = \frac{IE}{T}\int_0^T \operatorname{Sin} mt \,.\, \operatorname{Sin} (mt \pm \phi) \,.\, dt$$

or

$$w = \frac{EI}{2} \operatorname{Cos} \phi.$$

Substituting the *effective* values of the voltage and the current, as shown by the ammeter and the voltmeter (§ 36 *c*), we get

$$w = i_{eff}\,.\,e_{eff}\,.\operatorname{Cos} \phi. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Equation (3) shows that true power delivered to an alternating circuit depends not only upon the effective values of the current and the voltage, but also upon the phase angle between the two. The expression

$$i_{eff}\,.\,e_{eff}$$

is sometimes called *the apparent power;* the ratio of the true power to the apparent power, or $\operatorname{Cos} \phi$, is called *the power factor* (of the load).

It follows from the above considerations that in order to measure the true power in an alternating-current circuit, it is necessary to have an instrument which automatically accomplishes the integration required

by the expression (2) and gives the average value of w. Such instruments are called indicating wattmeters.

76. Electro-dynamometer Type Wattmeter. — A wattmeter of this type (Weston) is shown diagrammatically in Fig. 78; the electrical connections and the general view of the instrument are shown in Fig. 79. For the electro-dynamometer principle see § 40. The instrument has two stationary coils and a moving coil between them. The details of construction are similar to those shown in Fig. 34, except that stationary coils are substituted for permanent magnets.

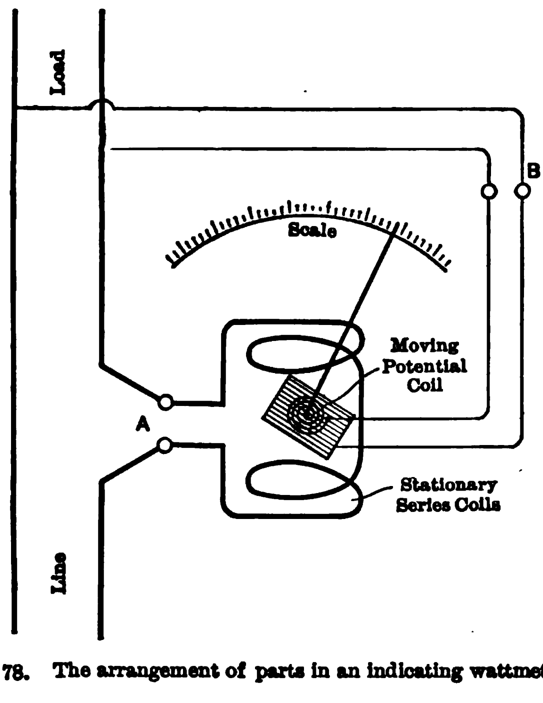

FIG. 78. The arrangement of parts in an indicating wattmeter.

The stationary coils consist of a few turns of heavy wire or strip connected in series with the circuit, as in an ammeter. The moving coil consists of many turns of fine wire, and is similar to the moving coil of D.C. voltmeters; it is connected across the circuit with a high non-inductive resistance (multiplier) in series with it. The instantaneous force of attraction between the coils is thus proportional to the product of current by voltage, or to the instantaneous power in the circuit. If the moving part of the instrument had no inertia it would vibrate with the fluctuations of the instantaneous values of energy.

But with usual frequencies of alternating currents these fluctuations follow in such quick succession that the moving element assumes a position corresponding to the *average* impulse: it automatically integrates the power over the cycle, according to expression (2).

The scale is divided directly in watts or in kilowatts (1 kilowatt = 1000 watts). The instrument is calibrated with standard direct-current ammeters and voltmeters, and may be used on either direct or alternating current. The large terminals *dd*, Fig. 79, are connected in

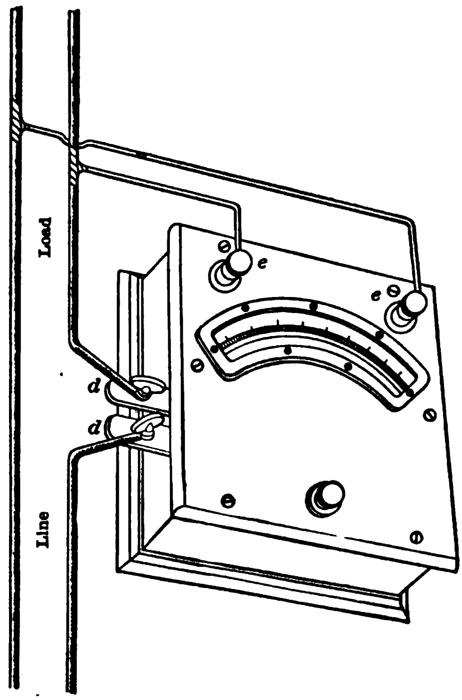

FIG. 79. External connections and general view of an indicating wattmeter.

series with the circuit in which it is desired to measure the power; the small terminals *ee* are connected across the line. The button shown below the scale closes the potential circuit when pressed down. This is a necessary precaution in order not to overheat the moving coil and the multiplier.

77. Compensation for Power Consumption in the Wattmeter Itself.—An indicating wattmeter, such as is shown in Fig. 79, consumes some power in its series and potential windings. The inaccuracy introduced thereby is in some cases sufficient to make necessary a

correction. It will be easily seen in Fig. 79, that the current flowing through the series winding of the wattmeter is a sum of the load current and of the current consumed in the potential circuit of the wattmeter itself. Therefore, the instrument indicates more power than is actually consumed in the load. The corresponding correction is

$$i^2R = \frac{E^2}{R}$$

where i is the current in the potential circuit, R the ohmic resistance of this circuit, and E is the line voltage.

Connecting the potential leads of the wattmeter on the "line" side of the series winding, brings in another inaccuracy; namely, the voltage across the potential terminals of the instrument is then higher than the load voltage, by the amount of voltage drop in the series winding of the instrument. If the resistance of the series winding is r and the load current is I, the corresponding correction is

$$I^2r.$$

It is usually preferred to have the wattmeter connected as in Fig. 79, and to correct for the loss of power in the potential winding. The reason is that it is more difficult to measure the resistance r of the series winding, and, moreover, it depends on the contact resistance at the terminals A.

Weston wattmeters are provided with a compensating winding, which makes a correction unnecessary, and thus simplifies the use of the instrument. Such a compensated wattmeter is shown in Fig. 80, the compensating coil being connected in series with the potential coil. When the load is zero, a current flows through the series and the potential windings of the wattmeter (Fig. 79), and causes the pointer to indicate some power, though in reality the power consumption is zero. The compensating winding gives a number of ampere-turns equal and opposite to that created by the series coils, and thus makes the pointer indicate zero at no load. The compensation is good at all voltages, since the current in the compensating coil is always the same as in the series winding (at no load). The potential circuit is completed between the terminals C and B, through the compensating coil, the movable potential coil, and a high resistance (multiplier) R. The terminals C and B are usually marked in Weston instruments "±" and "150 volts."

In cases in which the series winding and the potential winding are supplied from two independent sources, the compensating coil should be left out of the circuit, and the terminal D used, instead of C. The

terminal D is marked " Ind.," or independent, and is connected to the potential coil through a low resistance r equal to the resistance of the compensating coil. This is done in order to have the same total resistance between B and D, as between B and C. In this way the instrument calibrated between one pair of the terminals reads correctly between the other pair of the terminals.

The practical cases in which the "independent" terminal D should be used, instead of C, are:

(1) When the wattmeter is connected through series and shunt transformers (when connected to a high-potential circuit).

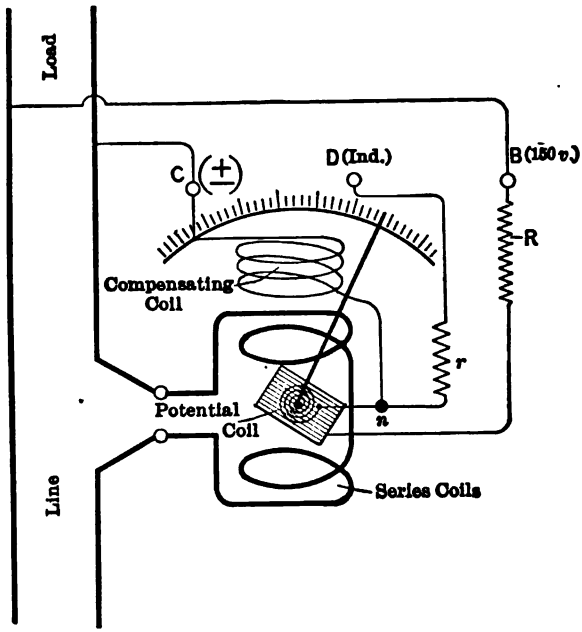

FIG. 80. Compensation for the power consumption in the wattmeter itself (Weston).

(2) When the instrument is calibrated with a separate source of current for the series winding. The latter is the case when a large storage cell is supplying the current, while a battery of small cells gives the required voltage. With this arrangement, large wattmeters are calibrated with a comparatively small expenditure of power.

78. Inaccuracy at Low Power Factors. — The above given theory of the wattmeter presupposes that there is no inductance in the potential

circuit, so that the current in the moving coil is in phase with the line voltage. In reality the coil and the multiplier have some small inductance, so that, strictly speaking, the current in the potential circuit lags slightly behind the applied e.m.f. The inaccuracy thus introduced is usually negligible especially at high values of power factor, but with very low power factors may become quite noticeable.

The influence of the power factor is shown in Fig. 81. I is the vector of the current; E_1 the vector of the applied e.m.f. with a low

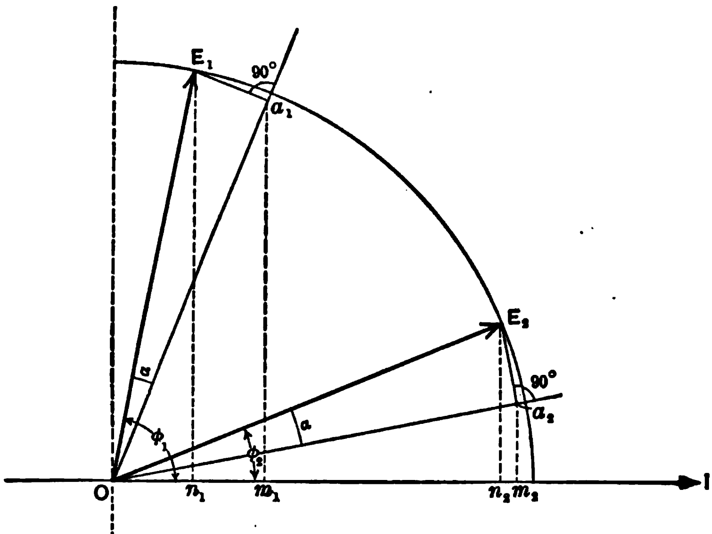

FIG. 81. Vector diagram, showing the influence of inductance in the potential circuit of a wattmeter.

power factor of the load (large phase displacement ϕ_1). If the potential circuit had no inductance, the current in the moving coil of the wattmeter would be in phase with E_1, and the indications of the instrument would be proportional to the working component $On_1 = E_1 \cos\phi_1$ of the voltage. In reality, the current in the potential coil is lagging behind E_1 by an angle α. The result is the same as if the applied voltage were reduced to Oa_1, with a working component Om_1. Applying the same reasoning at a high power factor corresponding to the applied voltage OE_2, the points n_2 and m_2 are obtained. It is easy to see that with the same current I, same voltage E and the same angle of lag α in the potential circuit, per cent error $n_1m_1 \div On_1$ is much larger at the low power factor than per cent error $n_2m_2 \div On_2$ at the high power factor. Knowing α, readings can be corrected, as in Fig. 81.

Under ordinary circumstances, and with good instruments, the inaccuracy due to this cause is negligible, but under extreme conditions a correction, as in Fig. 81, is necessary. Another way out of the difficulty is to measure the "wattless" power (Fig. 341); still another way is to measure the power by some means other than a wattmeter, for instance by a calorimeter, or by the three-voltmeter method (§ 109). A hot-wire wattmeter may also be used; see Roller, "Electric and Magnetic Measurements," p. 223.

79. Whitney Wattmeter.— The instrument (Fig. 82) is based on the same principle as the above-described Weston wattmeter, an electromagnetic torque being produced between the stationary series-coil *SS* and the moving potential-coil *MM*. The power is indicated by the angle of torsion necessary to bring the moving coil back to zero, and not by the direct deflection of the moving coil, as in the Weston instrument. In this respect the Whitney wattmeter is similar to the electrodynamometer shown in Fig. 39.

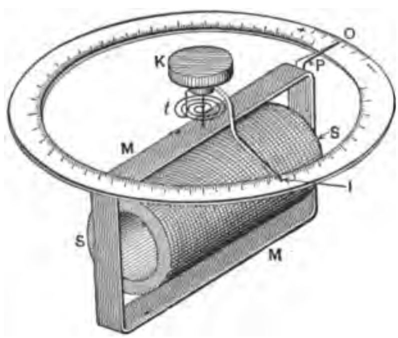

FIG. 82. The Hoyt (Whitney) wattmeter.

The instrument is connected to the line as in Fig. 78, the polarity being selected so that the pointer *P* deflects from *O* to the side marked +. Turning the knob *K* clockwise brings *P* back to zero; the angle is shown by the index *I*. The small scale on both sides of *O* permits one to read watts differing slightly from those shown by the index *I*; this is convenient on fluctuating loads. Suppose, for instance, the reading on the large scale be 125 watts, and the pointer *P* indicate 4 watts clockwise; the actual reading is then 121 watts. If *P* had shown 4 watts on the + side, the reading would be 129 watts.

80. EXPERIMENT 4-A. — Calibration and Study of Indicating Wattmeters of Electro-Dynamometer Type.— The instruments are described in §§ 74 to 79; they are calibrated with direct current, and may be used on either direct or alternating current. Connect the wattmeter under test to a direct-current line and provide a suitable load; connect into the same circuit an ammeter and a voltmeter which have been previously standardized. Begin the calibration with the largest load —

read volts, amperes and watts. Gradually reduce the load, taking similar readings. In connecting the wattmeter keep in mind the explanations of § 77 and avoid errors due to energy consumption in the instrument itself. To see the influence of this factor, use the "Ind." (independent, Fig. 80) terminal instead of the regular one and note the difference in the indications with the same load. See if the correction I^2R accounts for the discrepancy; try this with a large and a small load. Observe the influence of terrestrial magnetism by reversing both currents in the instrument and take an average of the two readings to eliminate this effect. This is necessary with direct currents only.

Having calibrated the instrument try it on an A. C. circuit; change if necessary the ammeter and the voltmeter. First measure a non-inductive load, preferably incandescent lamps; then connect some inductance in parallel with it (as in Fig. 120), keeping total current constant. You will find that the watts decrease gradually, while the apparent power (volts × amperes) remains the same.

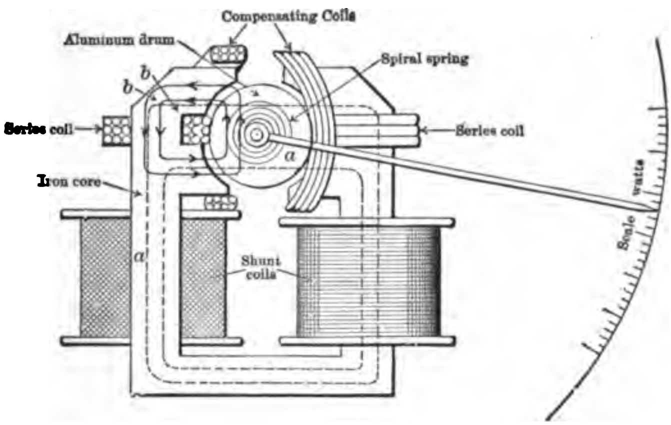

FIG. 83. An induction-type indicating wattmeter.

Report. Give a calibration curve in the form shown in Fig. 62. State your findings in regard to the energy consumption in the instrument itself and in regard to the influence of the terrestrial field. Give data showing that the true power is less than the apparent power when the load is inductive. Figure out the power factor of the load, according to equation (3) in § 75.

81. Induction Wattmeter. — An indicating wattmeter based on an entirely different principle is shown in Fig. 83. In its principle it is a

single-phase induction motor (§ 346) the armature of which is not allowed to revolve, but is merely deflected, overcoming the tension of a spring. The action is the same as in the induction-type instrument shown in Fig. 43, except that the split phase is produced by series coils carrying the line current, instead of a coil short-circuited upon itself. Moreover, the moving element is an aluminum drum and not a disk. This last difference is, however, not essential: there are induction ammeters and voltmeters on the market, with the moving part in the form of a drum, and vice versa. The shunt coil is connected across the line, in series with a high inductance (choke coil). Therefore the current in the shunt coil lags practically 90° behind the applied e.m.f., and so must also the flux (shown by dotted lines) produced by the coil. The series coil carries the line current and produces a flux in phase with it; this flux is shown by lines drawn in full.

When the current is in phase with the applied voltage the aluminum drum is threaded by two fluxes at 90° to each other geometrically and also displaced in phase by 90° electrically. These are exactly the conditions necessary for producing a revolving flux (see § 332). This flux induces secondary currents in the drum, and the drum tends to follow the flux. The action is proportional to the magnitude of both component fluxes; consequently it is proportional to the product "volts times amperes," or to the power in the circuit. If the current is out of phase, only its working component contributes to the revolving flux, being 90° out of phase with the shunt flux; the flux produced by the wattless component does not increase the torque exerted on the aluminum drum. Thus with any value of the power factor, the action on the moving part is proportional to true watts.

In reality the current in the shunt coil lags less than 90° behind the applied voltage, because of some ohmic resistance in the potential circuit. Nevertheless it is possible to keep the shunt flux in exact quadrature with the applied e.m.f. by placing on the poles of the iron core a "compensating" winding. The compensating coils are short-circuited upon themselves and act as the secondary of a transformer of which the shunt coil is the primary. The diagram (Fig. 84) explains the corrective action of the compensating winding. Let E be the vector of the applied voltage, and i_1n_1 the ampere-turns on the shunt field; they are not quite in quadrature with E. The ampere-turns on the secondary or compensating winding are represented by i_2n_2; they are not exactly in opposition to the primary ampere-turns, because of the resistance of the compensating coils and of the magnetic leakage between the two windings. The total ampere-turns which produce the magnetic flux F in the pole-pieces are represented by the vector in, which is a geo-

metric sum of i_1n_1 and i_2n_2. The number of turns and the resistance of the compensating winding are adjusted by trial so as to make the flux F to lag exactly by 90° behind the applied voltage E.

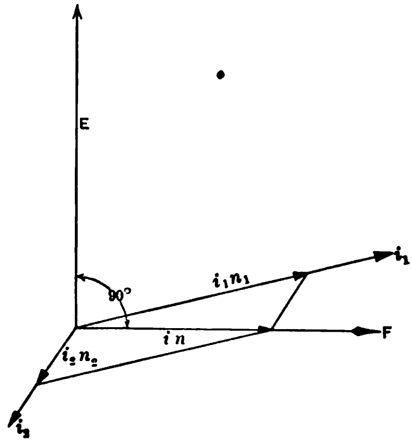

FIG. 84. Corrective action of the compensating coil of a wattmeter.

Induction wattmeters are robust, have quite a high torque, and are sufficiently accurate for ordinary practical purposes. Their accuracy is increased by their being usually provided with a long scale extending over 300°; a feature impossible in dynamometer-type wattmeters, unless a torsion knob is used (Fig. 82). Connecting the current and the potential coils in series or in parallel considerably increases the useful range of the instrument. Wattmeters of this type are built either as portable instruments or for switchboard service. For polyphase service two independent wattmeter movements are mounted on a common shaft, and the deflection on the scale measures total power of the system, with any distribution of load between the phases. With large outputs and high voltages, series and shunt transformers are used with wattmeters (Figs. 44 and 45).

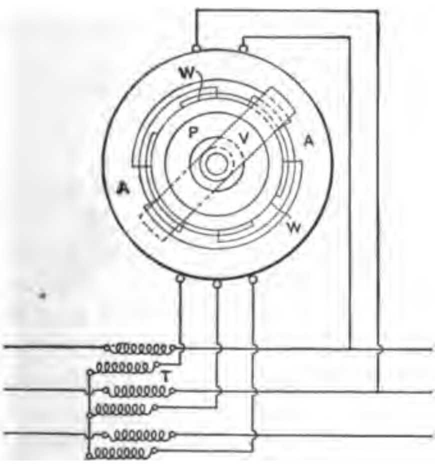

FIG. 85. The electrical circuits of the Westinghouse power-factor meter.

Induction wattmeters can evidently be used on alternating-current circuits only; moreover, their indications depend to some extent on the frequency of the supply. They are calibrated through the medium of a dynamometer-type wattmeter which in its turn is previously standardized with direct current.

82. Power-Factor Meter. — Some operating features of A. C. power

plants and transmission lines depend essentially on the power factor of the load. By having on the switchboard the necessary ammeters, voltmeters and wattmeters the power factor of the output can be easily calculated at any moment. But it is much more convenient to have an instrument which shows power factor *directly*, without any computation. The principle of one type of such power-factor meters is shown in Fig. 85. The device can be used on polyphase lines only; this is, however, no objection, because practically all transmission plants are either two-phase or three-phase.

The stationary part consists of a laminated iron core A, provided with a regular two- or three-phase winding, and connected to the line through the series transformers T. The moving part consists of a soft-iron vane V, of a shape shown in Fig. 86. The stationary winding produces a rotating magnetic field (§ 520) under the influence of which alone the vane would revolve as the rotor of an induction motor. But this vane is also actuated upon by a stationary coil P, connected across one of the phases of the circuit. The pulsating field produced in this coil weakens the revolving field in a certain direction, and leaves it intact in the perpendicular direction. The moving vane then assumes this direction of maximum magnetic field; its position is indicated by a pointer on the scale.

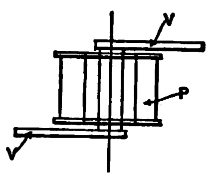

FIG. 86. The potential coil and the movable vane of the power-factor meter, shown in Fig. 85.

The currents in the polyphase winding of the instrument, being produced through the series transformers, are in phase with the line currents. The current in the coil P is in phase with the line voltage. Therefore the position of the vane will depend *on the phase relation* between the line current and the line voltage, or, which is the same, *on the power factor* of the load. The instrument is calibrated directly in per cent power factor, the calibration extending over all the four quadrants of the scale. This is necessary because currents may be leading or lagging, and the phase angle between them and the voltage will be less or more than 90 degrees, according to whether the machine is working as a generator or as a motor.

The power-factor meter is by no means an accurate measuring instrument; its indications are affected by the magnitude of the line current, and by the line voltage. But for a comparative judgment of the variations of power factor during the day it is a very useful instrument, and deserves its place on every well-equipped switchboard.

83. EXPERIMENT 4-B. — Study and Calibration of a Power-Factor Meter. — The instrument is described in the preceding sec-

tion. Provide a three-phase load, as in Fig. 405 or Fig. 413; have an ammeter, a voltmeter and a wattmeter connected into the circuit by means of a polyphase board (§ 49). Connect the power-factor meter as in Fig. 85 and apply the largest inductive load possible with safety. Read the four instruments and gradually increase the power factor of the load, keeping the same total current, until the load becomes non-inductive. Repeat the same test with two or three smaller values of current. If an over-excited synchronous motor is available the calibration may be extended on the quadrants corresponding to leading current.

Before or after the calibration investigate a few features of the construction of the instrument:

(1) Open the potential circuit and observe the vane rotate under the influence of the field produced by the series winding alone. Reverse two of the series leads, whereupon the vane will revolve in the opposite direction.

(2) Reverse the potential leads; the pointer will turn by 180 degrees. This corresponds to the change from output to input, in other words, from alternator to synchronous motor.

(3) The instrument is intended to be read with balanced load only; unbalance the load and see what effect this has on indications of the power-factor meter.

WATT-HOUR METERS.

84. Watt-Hour as a Unit of Consumption of Electrical Energy. — A certain amount of coal is required to generate electrical energy at the rate of one watt during one hour. The energy made use of by the consumer of electrical energy depends on the number of watts consumed, and on the time during which the power has been used. For these reasons it is proper to charge for electric power on the basis of watt-hour or kilowatt-hour consumption. A 16 candle-power incandescent lamp consumes about 56 watts; hence it uses during one hour 56 watt-hours of electrical energy. Two lamps, if burned half an hour each, or 4 lamps used a quarter of an hour each, also consume together the same amount of energy. Within certain limits it does not make any difference to the company supplying the power during what period of time a certain amount of energy is consumed. If the price is ten cents per kilowatt-hour, the cost to the consumer is in either case

$$10 \times \frac{56}{1000} = 0.56 \text{ cent.}$$

Expressed more accurately, the cause for measuring electrical energy in watt-hours, instead of simply in watts, is that one watt represents a certain amount of energy liberated or absorbed *in one second;* in other words, it is only a *rate* of expenditure of energy. This follows from the definition of watt, it being a product of "volt × ampere," where the ampere is a quantity of electricity *per second.* On the other hand, the energy contained in one lb. of coal is measured in B.T.U.'s, calories, joules, etc., units independent of time. Therefore watts must be multiplied by time in order to reduce them to the same physical conception, and to the same dimensions as the heat units.

Instruments which measure watt-hours energy consumed in a circuit during a certain period of time, are called watt-hour meters — sometimes they are referred to simply as "electric meters." The monthly bill of a customer is usually made up on the basis of indications of the watt-hour meter on his premises.

85. Types of Watt-hour Meters. — Watt-hour meters, in use at present, are of the motor type exclusively, a small motor being arranged to revolve at a speed proportional to the rate at which energy is passing through it. The number of revolutions is recorded on a dial; by knowing the constant of the meter this number of revolutions can be reduced to kilowatt-hours. In most meters the shaft of the motor is geared to the recording mechanism in such a way that the meter reads directly in kilowatt-hours.

Two types of *indicating* wattmeters are described above — dynamometer type (§ 76) and induction type (§ 81); to these correspond two types of watt-hour meters — commutator meters (Fig. 87) and induction meters (Fig. 92). A direct attraction between stationary and revolving coils is utilized in the first type, and such watt-hour meters may be used on either direct- or alternating-current circuits. Induction meters are based on the principle of the revolving magnetic field and can be used on alternating-current circuits only. With the advent of the induction meter, the commutator meter is relegated to direct-current circuits only, the induction meter being simpler and more accurate. The so-called Sangamo meter described in § 89 below, was produced as an attempt to do away with the commutator in direct-current watt-hour meters.

On D. C. circuits on which the voltage is kept practically constant, watts are proportional to amperes, and it is sufficient to measure ampere-hours, instead of watt-hours. Multiplying the former by the actual or agreed voltage of the supply gives watt-hour consumption. Electrolytic meters are to some extent used in such cases, especially abroad. The current flowing through the meter decomposes a certain

chemical contained in it. The amount of material decomposed is proportional to coulombs or ampere-hours which pass through the meter; the scale can be made direct-reading.

86. Commutator-Type Watt-hour Meters. — The Thomson commutator meter (Fig. 87) consists of a small direct-current, vertical shaft

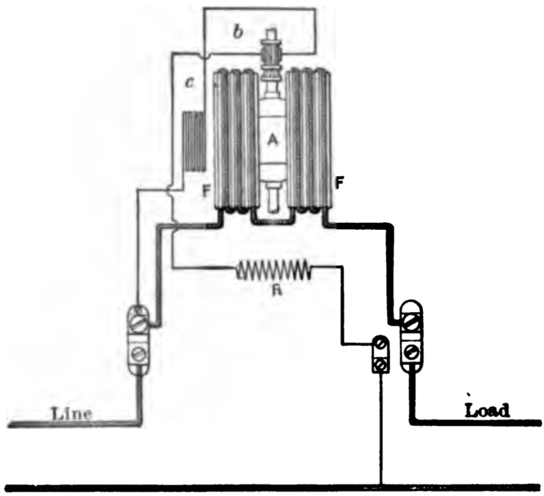

FIG. 87. The electrical connections in a Thomson watt-hour meter.

motor, without iron in its magnetic circuit. The armature A is connected across the line with some additional resistance R in series, according to the voltage of the supply; the fields F are in series with the line. Thus the current flowing through the armature is proportional to the line voltage, and the current flowing through the field is equal to the line current; hence the attraction between the field and the armature is proportional to the product "line voltage times line current," or proportional to the power delivered. In this respect it is similar to the indicating wattmeter shown in Fig. 78. Fig. 88 gives the general view of this meter. See also Note on page 115.

A motor connected in this way would run away without a load. To make its speed proportional to the power transmitted, the meter is provided with a Foucault-current brake, consisting of a copper or aluminum disk D mounted on the armature shaft and placed between the poles of permanent magnets MM. To understand the action of this brake, assume first that the meter has no friction; at the full rated load the armature revolves at a certain speed, determined by the counter-torque of eddy currents in the brake. Now if the load, or the product

volt-amperes, falls, say, to $\frac{3}{4}$ of its former value, the attraction between the field and the armature of the motor drops in the same ratio and the motor slows down. This decreases the eddy currents in the brake

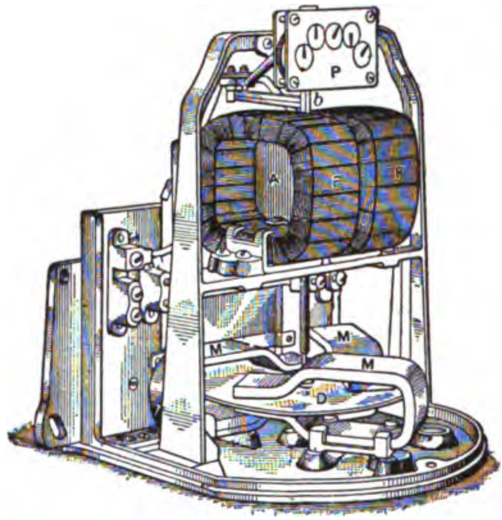

FIG. 88. A general view of the Thomson watt-hour meter.

(which currents are proportional to the speed); at $\frac{3}{4}$ of the initial speed the counter-torque is again equal to the motor torque. Thus, neglecting friction, the speed of the meter is proportional to the load, and it should register correctly at all loads.

The speed of the meter is usually adjusted so as to make it direct-reading, or at least have simple multiples as 2, 10, etc. This is done by adjusting the position of the permanent magnets of the brake so as to get the required amount of eddy currents induced in the disk *D*. A meter dial is shown in Fig. 89; with the position of the hands shown

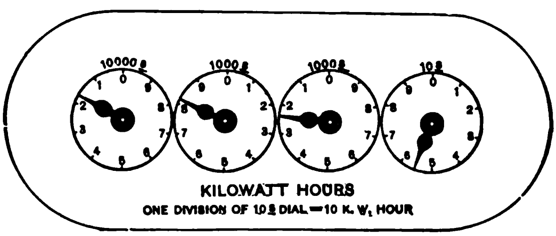

FIG. 89. The scale of a watt-hour meter.

there the reading is 18255 kw.-hours. If the reading next month is, for instance, 18490 kw.-hr. the consumption during the month was

235 kw.-hr., and at a price of, say, 10 cents per kw.-hr. the monthly bill will amount to $23.5.

It can be seen from Fig. 87 that one of the series or current terminals is used at the same time as one of the potential terminals. The connection is made inside of the meter so that only three leads come out of the cover.

87. Compensating for Friction. — Friction causes the meter to run slow on small loads; as in a great majority of cases meters run on light load most of the time, this would represent an appreciable loss to the company supplying the current. For instance, a 20-lamp (10 amp.) meter would not start at all (without the compensating device described below) if only one lamp of usual size were burning; this might induce some customer to leave a lamp permanently in the circuit.

To remedy this, a compensating coil c (Fig. 87) is provided in the armature circuit; the field produced by this coil gives an additional torque just sufficient to balance the friction of the meter. As it is impossible to predetermine the exact amount of friction, the more that it varies with the pressure of the brushes on the commutator, with the wear of the jewel supporting the shaft, etc., this compensating coil is made adjustable. The complete arrangement is shown in detail in Fig. 90. FF are the main field coils, C is the compensating coil. Its distance from the armature can be varied by means of the screws A and B and the guide D.

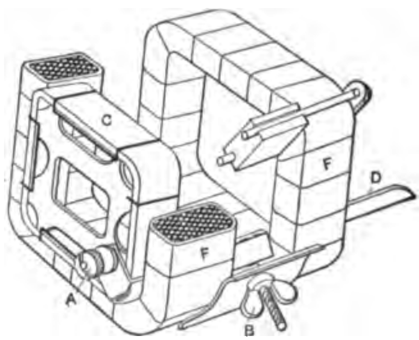

FIG. 90. The friction compensation in Thomson watt-hour meters.

In some meters the compensating coil is stationary, but is provided with several taps connected to the buttons of a dial. By means of a small lever more or less turns of the compensating coil may be introduced into the circuit, and in this way the amount of compensation varied at will.

If the meter is not sufficiently compensated, the company is losing money on light loads; if the meter is over-compensated, it *creeps* at no load and registers energy even when no current is used. This naturally leads to a complaint on the part of the customer; he refuses to pay the bill, becomes prejudiced against using electric power, and the company is again losing money. It is commonly appreciated now that honesty in regard to meter calibration and adjustment is the most

profitable policy on the part of illuminating companies, and the best advertisement for obtaining new customers.

88. EXPERIMENT 4-C. — Calibration of Commutator-Type Watt-hour Meters. — Watt-hour meters are calibrated by comparison with a good indicating wattmeter. One way is to hold a constant load until the reading on the dial of the watt-hour meter has changed by a reasonable amount. This, however, consumes too much time, and involves a considerable loss of electrical energy; therefore the following method is employed. A desired load is put on both meters and read on the indicating wattmeter, or on an ammeter and a voltmeter; the number of revolutions of the armature shaft of the integrating watt-meter during a minute or so is counted (use a stop watch). The reduction ratio of the recording train is usually an even number, for example 100, 200, etc., and knowing this ratio the wattmeter error can be easily calculated.

Suppose, for instance, that a constant load of 180 kw. was put on a watt-hour meter and maintained constant by means of an indicating wattmeter. Suppose that 15 revolutions of the armature disk be counted during 28 seconds, and that the reduction ratio of the recording gear be 1000 ÷ 1. If the value of one complete revolution of the pointer on the lowest dial is 100 kw.-hr. (see Fig. 89), the armature disk must complete one revolution while 100 ÷ 1000 kw.-hours, or 0.1 kw.-hr. is delivered to the load circuit. During the test, an energy equal to 180 × 28 kw.-seconds, or

$$180 \times \frac{28}{3600} = 1.4 \text{ kw.-hrs.}$$

has been delivered to the circuit. Therefore, the disk should have completed

$$1.4 \div 0.1 = 14 \text{ revolutions.}$$

In reality it made 15 revolutions; thus, at this particular load the meter runs about 7.1 per cent fast, and consequently registers 7.1 per cent more energy than is actually consumed.

Before beginning the calibration, investigate the action of the friction compensating device, and the behavior at light loads of the meter without the compensating coil connected in. The test consists in determining at what per cent of full load the meter can be made to positively start without danger of "creeping" at no load. Also try suddenly throwing off a heavy load and see if the meter stops in a short time. Sometimes a meter correctly adjusted on a testing rack begins to creep when put on a wall where it is subjected to jarring from the street

or from an engine working near by. Try the effect of slightly jarring the meter under test and see what margin should be allowed for this effect. *Before beginning the calibration proper, adjust the meter so that it reads as accurately as possible on light loads.*

(a) Calibrate the meter with direct current; begin with an overload of about 25 per cent and gradually reduce the load to zero.

(b) Then calibrate with alternating current at a high and at a low power factor, to see if the calibration constant remains the same. When running at a low power factor, the error caused by the self-induction of the potential circuit is more noticeable (see § 78). The following form of data sheet will be found convenient, especially if more than one meter are calibrated together.

Meter No.	Name	Type
" "	"	"
" "	"	"
" "	"	"
" "	"	"

Rated Volts	Rated Amps.	Gear ratio: one rev. of disk = ____ watt hrs.
" "	" "	" " " " " = ____ " "
" "	" "	" " " " " = ____ " "
" "	" "	" " " " " = ____ " "
" "	" "	" " " " " = ____ " "

				Wattmeter No. ____		Wattmeter No. ____		Wattmeter No. ____	
	Volts.	Amps.	Watts	Rev.	Sec.	Rev.	Sec.	Rev.	Sec.
Inst. No.									
Const.									

(c) Determine the torque per watt per unit weight of the moving element, and the friction-torque ratio as explained in § 92.

Report. (a) Plot calibration curves of the meter, for D. C. and A. C. Use current in per cent of full-load current as abscissæ, and per cent "slow" or "fast" as ordinates.

(b) Give your results as to light-load adjustment and creeping at no load.

(c) Give the specific torque and the friction-torque ratio of the meter.

(d) Mention features of construction different from those described above.

89. Sangamo Meter. — The above-described commutator meters have two drawbacks:

(1) The commutator with its brushes is liable to give trouble, or get out of order. This is particularly annoying in the case of watt-hour meters which are sealed and placed on customer's premises, and thus cannot be conveniently watched.

(2) Absence of iron necessitates a comparatively large number of turns on both windings; this makes the moving part heavy, increases bearing friction and causes jewel troubles.

These objectionable features are eliminated in watt-hour meters using mercury contacts (Ferranti, Sangamo). The Sangamo meter (Fig. 91) is essentially a homopolar electric motor, the armature D of which floats in mercury M and is subjected to a comparatively strong field of a shunt coil S provided with an iron core CC. The main current passes from the terminal T_1, through mercury M to the armature D, which consists of a copper disk, floating in the mercury; thence the current passes to the terminal T_2 again through the mercury. The energizing coil S is connected across the line. Thus the field of this meter is proportional to the voltage of the supply, and the armature current to the load current. The attraction between the armature and the field is thus proportional to volts times amperes, or to the power to be measured. This meter is provided with an eddy-current brake (not shown in Fig. 91) similar to that in Fig. 88, and so its speed is proportional to the watts consumed in the load circuit. Meters of this type intended for large currents are provided with outside shunts similar to ammeter shunts (Fig. 35). Friction is com-

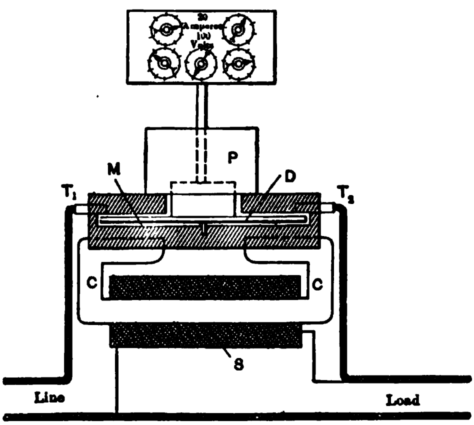

FIG. 91. The general arrangement of Sangamo watt-hour meter.

pensated for by an adjustable shunt, or by-pass, which allows a small current to flow constantly through the revolving disk, even at no load, thus creating an additional torque.

It should also be mentioned that the meter is provided with a pocket *P* of such a form that the mercury cannot possibly be spilled out whatever the position of the meter during transportation.

The Sangamo meter has no commutator or brushes, so that this source of trouble is removed; the armature is much simpler and lighter than that of commutator meters. Moreover, its weight does not rest on the lower bearing, since the disk is floating in mercury and is balanced so that there is just a little buoyancy upward. A strong field makes it possible to obtain a higher torque; this makes the action of the meter more positive on light loads. Part of the main current finds its path directly through the mercury, around the armature. This does not seem, however, to affect the accuracy of the meter, because the leakage current bears a constant ratio to the main current.

Sangamo meters can also be used on alternating-current circuits. As, however, they are based on the principle of direct attraction between the armature and the field, the field flux must be in phase with the armature current (at non-inductive loads), instead of being in quadrature with it, as in induction meters (§ 81). The shunt winding *S* possesses some self-induction; it is neutralized by connecting some capacity (a condenser) in series with it, to make the circuit practically non-inductive; the iron core must of course be laminated. In all other respects D. C. and A. C. Sangamo meters have the same construction.

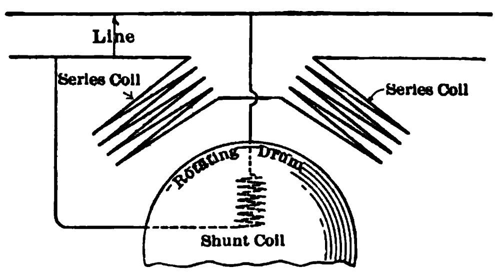

FIG. 92. Arrangement of coils in an induction type watt-hour meter.

90. Induction Meters. — Watt-hour meters for alternating currents operate on the principle of the revolving magnetic field, as single-phase induction motors. The general arrangement of the circuits

in one of the popular makes of such meters is shown in Fig. 92. The wattmeter has two windings, one in series with the line, another

FIG. 93. A view of the Fort Wayne watt-hour meter, showing the series and the potential windings.

FIG. 94. Revolving aluminum armature.

shunted across the line. Both windings are stationary, and produce together a rotating magnetic field in which a light aluminum armature revolves, as a squirrel-cage rotor of an induction motor. The two windings are clearly seen in Fig. 93; Fig. 94 represents the revolving part, or aluminum armature of the meter. The meter is similar to the indicating wattmeter described in § 81, and the explanation there given of its action is fully applicable here. In order to make the speed of the meter proportional to the load, an eddy-current brake is provided, as in commutator meters (§ 86). Only here it is not necessary to have a separate disk on which permanent magnets act. The same aluminum rotor can be used as the brake armature (Fig. 95);

FIG. 95. General view of a Fort Wayne induction type watt-hour meter.

this makes the meter less expensive and more compact than direct-current meters.

An induction meter of different construction is shown in Fig. 96. The lower coil is the series coil; *BB* are two potential coils. The

FIG. 96. Magnetic circuit of the Westinghouse watt-hour meter.

armature has the form of a disk (not shown in figure) and revolves in the space between the series and the potential coils. Friction is reduced to a negligible amount by having the moving element exceedingly light; moreover, the lower end of the shaft rests on a steel ball instead of a jewel, thus substituting rolling friction for the ordinary jewel friction.

FIG. 97. General Electric polyphase watt-hour meter.

Polyphase watt-hour meters are obtained by combining two single-phase meters. The two armatures are mounted on the same shaft and act on the same recording train, thus automatically adding together the indications of the two component meters. Some polyphase meters have separate armatures for each component meter; in some constructions, however (Fig. 97), both revolving fields act on the same aluminum disk. The brake magnet also acts on the same disk, thus the whole construction is made light and compact.

The method for connecting polyphase meters into a three-phase circuit is shown in Fig. 98; the scheme of connections is based on the fact that each of the three line wires, for instance *B*, can be considered as a common return wire for two other line wires *A* and *C*. The three upper connections belong to the upper component meter, the three lower connections to the lower meter. There are no electrical connections between the two component meters inside of the case. The upper meter registers the energy between the wires *A* and *B*; the lower meter, that between *C* and *B*. Three terminals are used instead of four, because one of the current terminals serves at the same time as a potential terminal (see Fig. 87). For the theory of power measurement in three-phase system, see § 430.

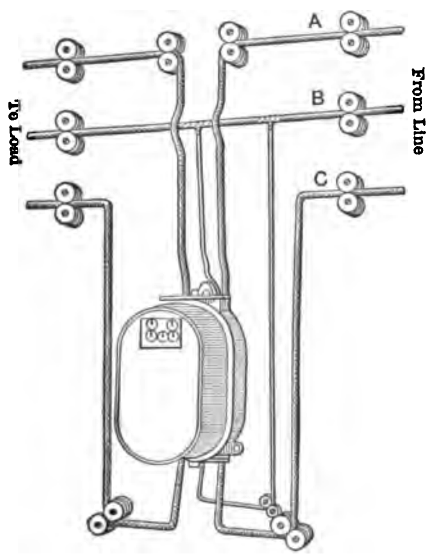

FIG. 98. Connections between a three-phase line and a polyphase watt-hour meter.

91. Correction for Phase-Angle. — A compensating winding is necessary in induction-type integrating wattmeters in order to bring the shunt flux in exact quadrature with the terminal voltage; the explanation for this is the same as given in § 81. In the meter shown in Figs. 92 and 93 this is accomplished by an additional shunt winding *G* (Fig. 99). *CC* is as before the series winding, *D* is the regular shunt winding connected across the line through a reactance coil *I*. The compensating coil *G* is connected across a few turns of the reactance coil *I* and is placed inside the shunt coil *D*, on a separate iron core. Resistance *H* in series with the compensating coil (lagging resistance) is adjusted so that the meter stands still at a full inductive load; this is a check for the compensation.

A third winding *E* is shown, short-circuited upon itself through an adjustable resistance *L*. This winding makes possible the use of the same meters with two standard frequencies: 60 cycles and 140 (or 133) cycles. When the meter is used on a high-frequency circuit, the coil *E* is inoperative; but when the meter is connected into a 60-cycle circuit the compensation offered by the coil *G* is not sufficient. Then

the circuit of the coil E must be closed, and the resistance L adjusted until the meter again stands still at a purely inductive load.

It would be hardly possible in practice to obtain a load at the power factor zero; therefore this adjustment is made on a two-phase circuit. The series winding of the meter is connected to one phase through a non-inductive load; the potential winding is connected to the other phase, which is exactly in quadrature with the first phase. In this way conditions are created that would take place in a purely inductive circuit.

In the meter shown in Fig. 96 compensating coils are wound on the same spools with the shunt coils B, and are short-circuited upon themselves through a resistance. This resistance can be adjusted by means of the slide-contact A so as to bring the shunt flux into the exact quadrature position.

In describing commutator meters a friction compensating winding or the light load adjustment (§ 87) was mentioned. Such a compensation is of much less importance in induction meters, since their moving element is lighter, and the torque per unit weight of the moving element much higher, so that the influence of the pivot friction is not so marked. The necessary compensation in the meter shown in Fig. 99 is obtained by making the field initially somewhat unsymmetrical, so as to give the armature a one-sided pull, just sufficient to balance the friction. Namely, the phase-correcting coil G is wound on a movable arm A, and this arm can be set in such a position that the meter will start at a certain small percentage of full load. The meter shown in Fig. 96 has no friction compensation whatever; the moving part is supported by a steel ball, and the friction is reduced to a negligible amount.

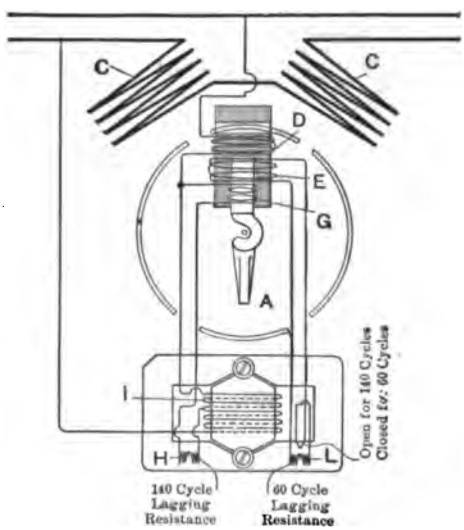

FIG. 99. Phase adjustment in an induction-type watt-hour meter.

92. Torque and Friction. — It is now generally agreed that a watt-hour meter is better the higher its torque per unit of weight of the

moving element. This is because the disturbing influence of the pivot friction is easily overcome, and the meter registers more accurately at light loads. There is a special instrument on the market, the so-called *torque balance*, by means of which the torque on the shaft of a meter can be directly measured in gram-centimeters, and two meters of different make compared.

The instrument is shown diagrammatically in Fig. 100. A light arm T is clamped to the shaft S of the meter under test, and is connected by a link L to a sensitive balance GH. The balance has a

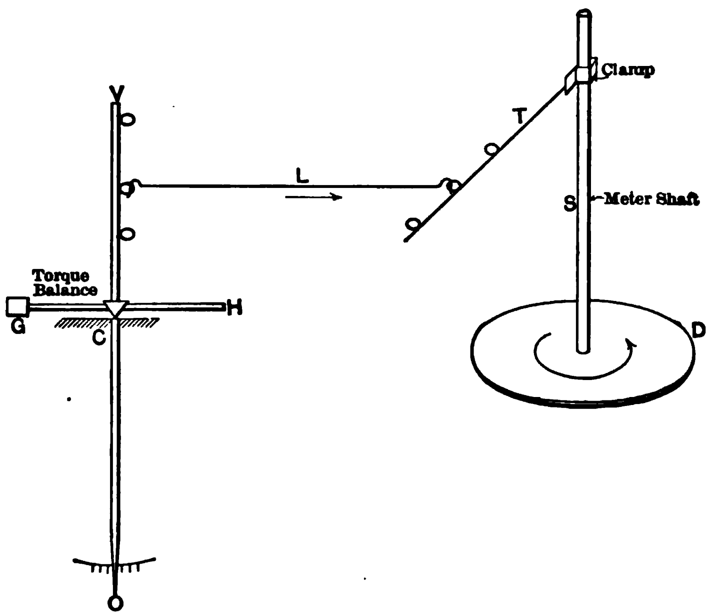

FIG. 100. A torque balance for testing watt-hour meters.

knife-edge support at C; the position of equilibrium is indicated by the pointer CO. A definite weight G is attached to the balance, causing it to tip toward the left. Then the meter is loaded electrically until the pull on the link L brings the pointer O back to zero. The critical load is measured on an indicating wattmeter; the mechanical torque is calculated from the weight G and the leverage $TLVC$. From these data the torque is calculated per watt of load and per ounce weight of the revolving part of the meter, supported by the lower bearing. This gives a basis for the comparison of competitive meters of similar construction. The rods V and T are provided with several

loops, so as to vary the torque in steps; two weights are supplied with the instrument, to cover a wide range of meters to be tested.

Meters can also be compared in this respect by determining their so-called *friction-torque ratio.* The friction compensator is adjusted at no-load so that the meter is just balanced, i.e., so that it will creep under the slightest vibration. When this is done, a load is applied equivalent to the full capacity of the meter and the speed of the revolving part measured. Then the friction compensator is removed and the speed measured again at the same load. The percentage decrease in speed is proportional to the friction-torque ratio; thus two per cent would mean a friction-torque ratio of 1: 50; one per cent 1: 100, etc. The higher this ratio, the better is the meter, at least as regards the disturbing influence of its friction.

93. EXPERIMENT 4-D. — Calibrating Induction-Type Watt-hour Meters. — For instructions see Exp. 4-C above. In addition to the tests specified there, it is interesting to calibrate one of the induction meters at various frequencies and with different wave-form. Theoretically the calibration must differ under these circumstances, but it is claimed for good modern meters that they are "practically" accurate within certain limits of wave-form and frequencies. It is not necessary to repeat the complete calibration curves; one or two points accurately observed are sufficient to enable the observer to judge if the calibration remain the same. When calibrating an induction meter, it is advisable to take at least three separate curves: at non-inductive load, at a moderate load of constant power, but varying power factor, and at a load of constant-current value, with varying power factor. There are meters on the market, which register correctly at non-inductive loads only, and run too slow at inductive loads.

94. Wright Maximum-Demand Indicator. — The actual cost of supplying a certain number of kilowatt-hours of power to a customer depends on the rate at which he consumes his energy. A customer who uses one kilowatt regularly for eight hours a day is more desirable to the operating company than another who uses 4 kilowatts for two hours. The amount of energy per month is the same in both cases; but the first customer requires less capacity of the generating apparatus and a smaller transmission line than the second one; he also causes smaller fluctuations of the load. Therefore the company may give him a better rate per kilowatt-hour. This principle of "discrimination" in charging for electrical energy is used in some cities where the customer is charged so much per kilowatt-hour of the actually consumed energy, and then an extra charge is made for each kilowatt

of his *maximum demand.* Instruments for measuring the maximum load or maximum demand during a month, or other agreed period of time, are called maximum-demand indicators.

The Wright maximum-demand indicator, used to some extent in this country and in England, is shown schematically in Fig. 101. It records the maximum current which has passed through it at any time since it was last set. A liquid is hermetically sealed in a glass tube having a bulb at each end. Around the left, or heating bulb, is placed a band of resistance metal, through which passes the current to be

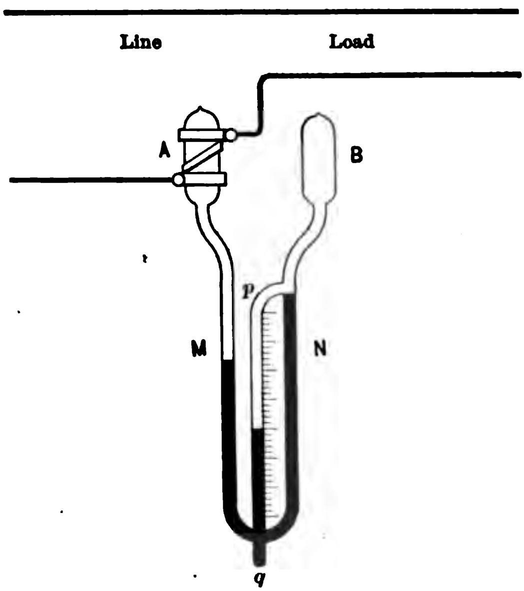

FIG. 101. Wright maximum-demand indicator.

measured. The passage of the current heats the air in the bulb, and the expansion of the air forces the liquid up into the right-hand side of the tube, causing it to overflow into the middle or indicating tube. The liquid deposited in the indicating tube remains there until the indicator is reset. The glass tube is carried on a backing, so hinged that the meter can be reset by tipping the tube and allowing the liquid to run out of the indicating tube into the side tubes. It is the difference in temperature of the air in the two bulbs, that causes the indicator to register. Any change in the temperature of the external air causes equal air expansion in both buibs, and hence does not affect the reading.

The instrument is purposely made slow-acting; standard indicators are so designed that if the maximum load lasts only five minutes, the meter will register about 80 per cent; if ten minutes, 95 per cent, and the full 100 per cent is registered when the load has continued about forty minutes. In this way the customer is not penalized for short overloads which do not inconvenience the supply station in any way.

95. EXPERIMENT 4-E. — Testing Maximum-Demand Indicators. — The test consists in calibrating the scale of the instrument for loads carried indefinitely (more than 40 minutes). While this is being done, per cent indication may also be determined for loads carried for shorter periods of time. Begin with a slight load and read the level of the fluid in the middle tube say every five or ten minutes until it becomes stationary. Tip the instrument over to reset the liquid, and repeat the same experiment with a somewhat larger load, etc. The left bulb must be cooled off before putting on a load.

Report. Plot a calibration curve for the final levels of the fluid, and a few curves showing per cent indication on loads carried for a shorter time.

NOTE TO PAGE 101. It is essential for the understanding of the working of the Thomson watt-hour meter to keep in mind that the resistance of the armature is very low as compared to the resistance *R* in series with it. Moreover, on account of the magnetic brake, the meter runs at very low speeds, even on overloads. Consequently, the counter-e.m.f. of the armature is negligible, and the current through the armature is practically equal to the line voltage divided by the resistance *R* plus that of the armature. The speed of the meter is determined by the main current, which excites the stationary field. These conditions are altogether different from those obtaining, say, in an ordinary shunt motor, in which the counter-e.m.f. is practically equal to the line voltage; in this case the current through the armature varies greatly with small variations in speed.

With the magnetic brake removed, the meter acquires a very high speed. This speed is determined by the condition that the torque of the meter is equal to that of the mechanical friction at this speed. As the speed increases, the counter-e.m.f. of the meter cuts down the armature current and thus reduces its torque. Therefore, at a certain high speed the two torques balance each other.

CHAPTER V.

REACTANCE AND RESISTANCE IN A. C. CIRCUITS.

96. Physical Conception of Inductance.* — When a current flows through a conductor, a magnetic field or flux is created around it. As long as the current remains constant, this field does not react in any way upon the electric circuit. But when the current varies, the flux also necessarily changes; in doing so it induces in the conductor an electromotive force, in other words, reacts on the circuit and affects the rate of change of the current. This induced e.m.f., in accordance with the fundamental law of electromagnetic induction, has such a direction as to oppose the change in current, consequently to retard the change in flux. The action is very much as if the magnetic field had some kind of inherent *inertia.*

Sir Oliver Lodge gave the following striking picture, or analogy of this phenomenon. Imagine the magnetic field surrounding a conductor as consisting of whirls in ether driven by the current; assume these whirls to be endowed with some inertia. As long as the current is steady, the whirls are spinning at the same speed, and the effect of their inertia does not come into play. If now the applied e.m.f. be reduced, tending to reduce the current, the whirls by virtue of their inertia tend to spin at the same speed, and thus oppose the decrease of current. The current gradually decreases, and the field returns some of its stored energy to the source of the e.m.f. On the contrary, should the current be increasing, the whirls oppose its rise; the applied e.m.f. has to perform some additional work in accelerating the whirls. The opposing action of the whirls, or of the magnetic field, is stronger, the greater the flux; also the quicker occur the changes in the applied e.m.f. (the greater its frequency). This is analogous to the reaction of a heavy fly-wheel driven at a non-uniform speed — the reaction is proportional to the inertia of the wheel, and to the rate at which it is accelerated.

Whatever the explanation of the phenomenon, the observed fact is

* The property of conductors called *reactance* is a composite quality which includes the frequency of the circuit, and a physical property of the conductor itself, called its inductance. Therefore, in order to understand reactance, it is necessary first to form a clear physical conception of inductance.

that electrical conductors oppose changes in current by the generation of a. counter-e.m.f. *This reaction of conductors, expressed numerically, is called their inductance.* The reason for the name is that the reaction consists in "inducing" a counter-e.m.f. The practical unit of inductance in the volt-ampere-ohm system is called the henry. *An electrical device is said to have an inductance of one henry if one volt of counter-e.m.f. is induced in it when the current changes at a rate of one ampere per second.* The older name for inductance is "the coefficient of self-induction."

97. Difference between Inductance and Ohmic Resistance. — The presence of inductance in an alternating-current circuit necessitates an increase in the applied e.m.f. in order to produce the same current; similarly, an increase in resistance has the same effect. Thus, it may at first seem that, from a practical standpoint, resistance and inductance produce the same effect on the relations in the circuit, and do not need to be distinguished. There is, however, a vast difference between the two, as a consideration of the following points will show:

(1) Ohmic resistance is noticeable to the same extent whether current is steady or variable; the drop caused by it is at any moment proportional to the *instantaneous value* of the current. Inductance becomes apparent only when the current is varying; the induced e.m.f. or the resulting drop in potential being proportional to the *rate of change* of the current, and not to its absolute value.

(2) Resistance is due to some molecular friction in the conductor itself; inductance is caused by the inertia of the magnetic flux surrounding the conductor.

(3) Energy spent in overcoming ohmic resistance is converted into heat, and is lost electrically. Energy applied for overcoming inductance is stored in the form of electromagnetic energy of the field, and is periodically given back to the circuit through the medium of induced e.m.f.

(4) Ohmic resistance does not change with the shape of a conductor; inductance depends essentially on the form of the conductor: A wire, whether straight or wound into a coil, has the same ohmic resistance, while its inductance in the second case is increased many times because of the concentration of magnetic flux.

98. Inductance and Reactance. — In many practical problems inductance is treated in connection with alternating-current circuits of a constant frequency. It is convenient, therefore, to combine the frequency factor with the value of inductance; this simply means a change in the unit and the dimension of the quantity, which expresses the inertia of the magnetic field. The new physical quantity is called

the *reactance* of a circuit or of a device, and like ordinary resistance is expressed in ohms.

The following considerations lead to the conception of reactance. According to the foregoing definition of inductance, the applied voltage necessary for overcoming the effect of an inductance of L henrys is

$$e = L\frac{di}{dt} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $di \div dt$ is the rate of change of current with the time. This voltage e can be properly called the instantaneous inductive drop of voltage in the conductor possessing the inductance L. The voltage e is at any instant equal and opposite to the counter-e.m.f. induced in the conductor by the varying magnetic flux.

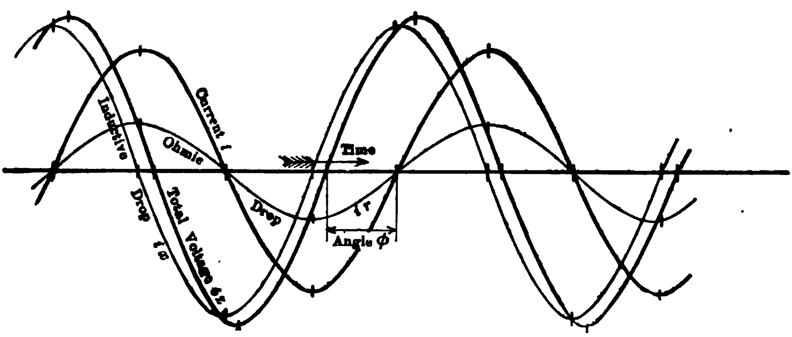

FIG. 102. Instantaneous values of current and voltages in an alternating-current circuit containing resistance and inductance.

Let the current vary according to the sine law, Fig. 102, at a frequency of n periods per second. The instantaneous values of the current may be expressed by the formula

$$i = I \operatorname{Sin} 2\pi nt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where I is the amplitude of the wave, and t is time in seconds. Substituting (2) into (1) we obtain the following value for the inductive drop:

$$e = 2\pi nLI \operatorname{Cos} 2\pi nt \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

This result interpreted means that a sinusoidal current sets up a sinusoidal counter-e.m.f. of the same frequency and of the amplitude

$$E = 2\pi nLI.$$

Denoting $$2\pi nL = x \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

we get $E = xI$; the same relation holds true for the effective values of current and voltage (see § 36 c); thus we obtain

$$E_{eff} = xi_{eff} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The quantity x is called the *reactance* of the coil, or of any other electrical device under consideration. Equation (5) shows that reactance, being a ratio of voltage to current, is expressed in ohms like ordinary resistance. It will be seen from (4) that reactance is a composite conception; its value depends on the inductance of the device, and on the frequency of the supply. As frequency usually remains constant in practice, reactance also remains constant (save when the conditions surrounding the conductor are changed).

Pulsations of current i and of voltage e do not reach their maxima simultaneously; the current passes through its zero value when the e.m.f. reaches its maximum, and vice versa. This is shown by the equations (2) and (3), for — while the current is expressed by a sine function — the voltage varies according to a cosine function. The two waves are shown in their relative phase positions in Fig. 102; see the curves marked "current i" and "inductive drop ix." The waves are said to be displaced in phase by 90 electrical degrees, since

$$\text{Sin } 2\pi nt = \text{Cos } (90° - 2\pi nt).$$

The above discussion shows the convenience of using reactance x instead of inductance L, and the relation between the two.

99. Experimental Determination of Reactance. — Reactance of a coil AB of low resistance (Fig. 103) may be determined experimen-

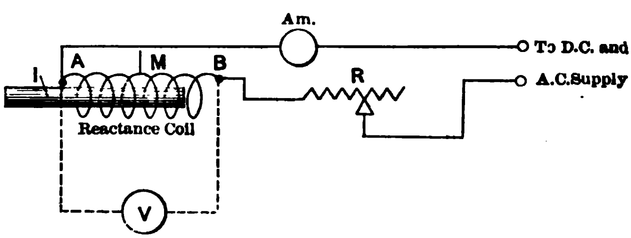

FIG. 103. Resistance and reactance in series.

tally, by measuring the current flowing through the coil and the A. C. voltage at its terminals. The reactance is equal to the ratio of the voltage to the current, according to equation (5). The current is measured on the ammeter *Am.*, the voltage by the voltmeter V connected across the terminals of the coil. The rheostat R is for the purpose of regulating the current.

An iron core I is shown within the coil; the presence of iron intensifies the flux produced by the coil, and thus greatly increases its reactance. By moving the core in and out the reactance may be varied

within wide limits. This method is often used for regulating current in A. C. circuits.

Three factors influence the accuracy of determination of reactance by this method: The ohmic resistance of the coil, the iron loss in the core (hysteresis and eddy currents), and higher harmonics in the supply voltage. These factors may either be kept down by a suitable

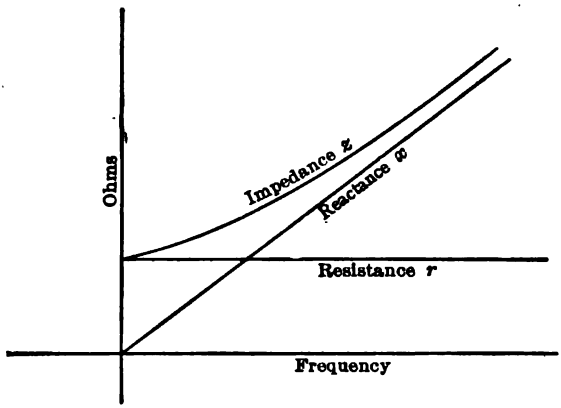

FIG. 104. Influence of frequency on reactance and impedance (resistance and inductance are kept constant).

choice of conditions, or their influence may be determined and corrected for, as is explained below.

100. Factors which Affect the Value of Reactance. —The reactance of a coil depends on the following factors:

(a) Frequency of the supply (Fig. 104).
(b) Presence of iron (Fig. 105).
(c) Intensity of current (Fig. 106).
(d) Number of turns in the coil.

In these diagrams the student is asked to pay attention, for the time being, only to the curves marked "Reactance x." It will be seen from these curves that:

(a) Reactance is directly proportional to the frequency of the supply, in accordance with the definition of reactance; see equation (4).

(b) Reactance depends essentially upon the presence and the position of the iron core, or plunger. The reactance decreases as the plunger is drawn out of the coil; the limiting value is that which the coil has without iron.

(c) With iron, the value of reactance depends on the intensity of the current flowing through the coil. This is because the magnetic

flux is *not* proportional to the current, the iron approaching its saturation limit (§ 121). The reactance reaches its maximum at the point

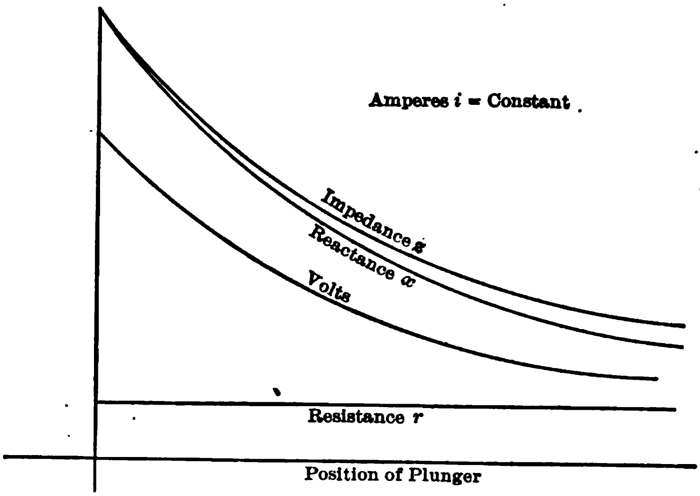

FIG. 105. Influence of the position of the plunger (Fig. 103) on reactance and impedance of the circuit.

of maximum permeability of iron, in other words, where the flux per

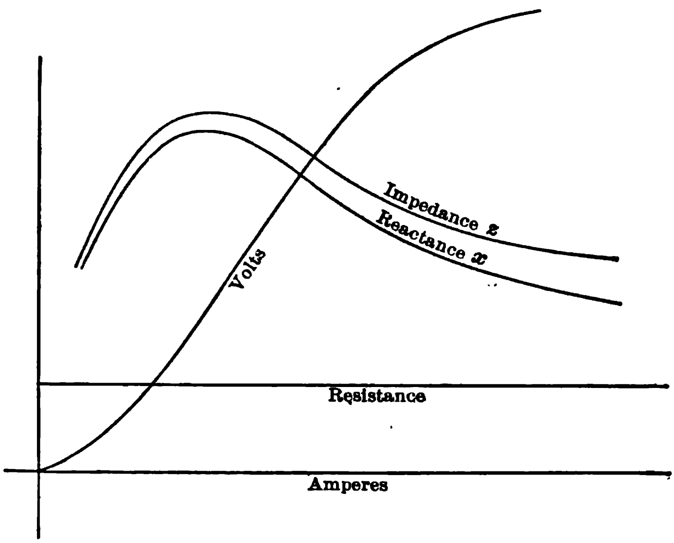

FIG. 106. Influence of the magnitude of current on the reactance of a coil (effect of saturation in iron).

1 ampere of current is a maximum. Without iron, there is no reason why reactance should depend on the value of the current, as both the

flux in the coil and the applied voltage are proportional to the current.

(d) The reactance of a coil is proportional to the square of the number of turns in series, other factors being identical, as is evident from a consideration of two coils. The two coils under comparison should have the same outside dimensions and the same space available for winding. Let one of the coils be wound with a finer wire, so as to accommodate m times more turns in the same space; assume, that the currents in the two coils are adjusted so as to produce equal fluxes in the respective cores. Let the induced voltage and the current in the first coil be E and I respectively — those in the second coil E' and I'. If the flux in the second coil is the same as in the first, I' must be $= I \div m$, in order to have the same number of exciting ampere-turns. The flux in the second coil is interlinked with m times more turns than an equal flux in the first coil; consequently $E' = mE$. Thus, the reactance of the second coil

$$x' = \frac{E'}{I'} = \frac{mE}{I \div m} = \frac{m^2 E}{I} = m^2 x,$$

where x is the reactance of the first coil. This proves that reactance increases as the square of number of turns. With the same number of turns, reactance increases as the cross-section of the coil, or at least as the cross-section of its iron core, for the reason that the flux produced by the coil increases in this proportion.

101. EXPERIMENT 5-A. — Study of a Reactance Coil without Iron. — The influence on reactance of frequency and of the number of turns, as discussed in the preceding article, may be conveniently studied on a coil without an iron core. The connections are as shown in Fig. 103; for the experiment a coil with a considerable number of turns of heavy wire should be used in order to have an appreciable inductance with a negligible resistance. (a) First investigate the influence of frequency. Connect the circuit to the terminals of an A. C. generator the speed of which may be varied at will. Keep the current through the coil constant, and measure the voltage across its terminals at various frequencies of the current. Take readings with two or three different values of the current. (b) Investigate the influence of the number of turns. It is convenient for this purpose to have a coil wound with two or more wires in parallel. By using separate sections of the winding, or combining them in series and in parallel, different numbers of active turns are obtained. The experiment may be performed at a constant frequency; the reactance should

be determined with several different values of current. (c) In cases where inductance is harmful, coils are wound *non-inductively*, or so as not to produce any magnetic flux. This is accomplished by connecting two halves of a winding so that each tends to produce a magnetic flux in a direction opposite to that of the other. Try this experimentally by sending a current through the coil with two sections of the winding connected in opposition. If the coil has only one winding, take a tap M (Fig. 103) as one terminal, and use the points A and B connected together as the other terminal. Before putting on current, insert enough resistance R to prevent an inrush of current. You will find the voltage drop across the coil very small, and consequently its reactance low.

Report. Plot values of reactance in ohms to cycles (of frequency) as abscissæ; figure out the inductance of the coil (in henrys) according to formula (4). Give the results showing that inductance increases as the square of the number of turns. Describe the experiment with the coil wound non-inductively.

102. EXPERIMENT 5-B. — Study of a Reactance Coil with an Iron Core. — The factors to be investigated are enumerated in § 100. The influence of the frequency and of the number of turns may be omitted, if experiment 5-A has previously been performed. To investigate the influence of the position of the plunger, first remove it (Fig. 103), and raise the current in the coil to its maximum safe value. Then gradually move the plunger in, at the same time cutting the resistance R out of the circuit, so as to keep the current constant (Fig. 105). Another set of curves may be taken, keeping the voltage across the coil constant, and allowing the current to drop as the plunger is inserted into the coil.

To investigate the influence of the intensity of current (Fig. 106), shove the plunger into the coil and gradually increase the current by regulating the rheostat R; read volts and amperes. Repeat the test with two or three different positions of the plunger.

Report. Plot curves showing variation of the reactance of the coil with the position of the plunger and with the intensity of the current in the coil, as in Figs. 105 and 106. Explain the character of the curves.

103. Impedance, or Combination of Reactance and Resistance. — Reactance coils have been considered heretofore as devoid of ohmic resistance, or at least having a negligible resistance. In many practical cases, however, the ohmic resistance of a circuit is of equal, if not of greater importance, than the reactance. It is necessary, therefore,

to investigate the combined action of a reactance having a resistance in series with it.

Experience and theory show, that a reactance x and a resistance r connected in series, as in Fig. 107, cannot be added arithmetically,

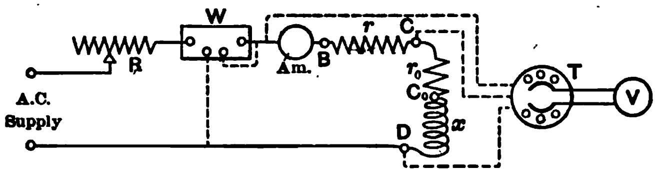

FIG. 107. Diagram of connections for investigating electrical relations in a circuit containing resistance and reactance in series.

though both are expressed in ohms. They must be added geometrically, at right angles, as in Fig. 108. For instance, let an inductance of 4 ohms be connected in series with a resistance of 3 ohms. To force

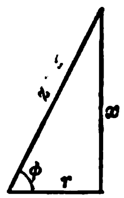

FIG. 108. Geometrical addition of a resistance and a reactance, the result being an impedance.

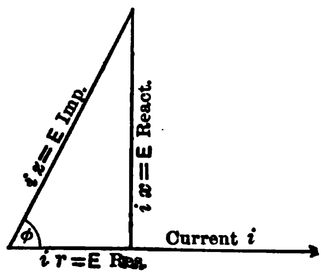

FIG. 109. The triangle of voltage drop, corresponding to Fig. 108.

a current of 10 amperes through the reactance alone an e.m.f. of 40 volts is necessary; to force the same current through the resistance alone, 30 volts are required. But when the two are connected in series, only 50 volts are necessary, instead of 40 + 30 = 70 volts. In other words, the combined action of 4 ohms and 3 ohms is seemingly equivalent to 5 ohms, and not to 7 ohms.

This peculiar relation can be explained by means of the equations established in § 98. When a coil — in addition to an inductance L — has some ohmic resistance r, the e.m.f. necessary to be applied at its terminals, in order to produce a current i, is

$$e = L\frac{di}{dt} + ir \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (6)$$

compare with equation (1). Substituting i from (2), and remembering the relation (4), we obtain

$$e = xI \operatorname{Cos} 2\pi nt + rI \operatorname{Sin} 2\pi nt \quad . \; . \; . \; . \; . \; . \quad (7)$$

This shows that the applied voltage at any moment is a sum of two voltages, each varying as a sine wave (Fig. 102). The wave of the inductive drop ix is the same as before; the wave of the ohmic drop ir is in phase with the current, both being represented by the same sine function. The total voltage $e = iz$ is also represented by a sine wave, for the sum of two sine waves of the same frequency is also a sine wave.

It will be seen from Fig. 102 that the amplitude of the wave marked "total voltage" is less than the sum of the amplitudes of the two component waves. Its phase position is also intermediate between the two. We may express this voltage by

$$e = zI \operatorname{Sin} (2\pi nt + \phi) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where z and ϕ are two new quantities which determine the magnitude and the position of the resultant e. Equating (7) and (8) we obtain

$$z \operatorname{Sin} (2\pi nt + \phi) = x \operatorname{Cos} 2\pi nt + r \operatorname{Sin} 2\pi nt \quad . \quad . \quad . \quad (9)$$

This relation is true at any moment t; applying it first for $nt = 0$, and then for $nt = \frac{1}{4}$, we obtain

$$\left.\begin{aligned} z \operatorname{Sin} \phi &= x \\ z \operatorname{Cos} \phi &= r \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

whence

$$\left.\begin{aligned} z &= \sqrt{x^2 + r^2} \\ \tan \phi &= x \div r \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

For given values of x and r, the values of z and ϕ may either be calculated from (11) or constructed as in Fig. 108. The "combined resistance" z is called the *impedance* of an apparatus or of a circuit; it is thus equal to the geometrical sum, and not to the arithmetical sum, of the component resistance and reactance in series.

Returning now to the above numerical example, we see that a 4-ohm reactance and a 3-ohm resistance act together as an impedance $z = \sqrt{4^2 + 3^2} = 5$ ohms. The equation (8) may be represented symbolically thus:

$$E_{eff} = zi_{eff} (\phi) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

where (ϕ) means that the wave of the current lags behind that of the applied voltage by the angle ϕ (Figs. 102 and 109). This equation compared to the equation (5) clearly indicates the influence of an ohmic resistance in series with a reactance.

104. EXPERIMENT 5-C. —Study of a Reactance Coil with an Appreciable Ohmic Resistance. —We assume now that the coil A-B (Fig. 103) has an appreciable ohmic resistance r. For experimental purposes, it is better to have the coil itself of a negligible resistance, but

have some resistance connected outside the coil, so as to be able to vary it (Fig. 107). The purpose of the experiment is: (1) To prove that a resistance and a reactance in series must be added geometrically; (2) To investigate the influence of the factors enumerated in § 100, as modified by the presence of resistance. To prove the triangle of resistances, Fig. 108, send an alternating current through the coil and the resistance connected in series. Measure the current and the voltage and determine the impedance z as the ratio of the voltage to the current, according to equation (12). Then measure the reactance x of the coil alone, also as a ratio of volts at its terminals to amperes flowing through the coil. Finally put on a direct current, and measure the ohmic resistance r. The three quantities thus determined must

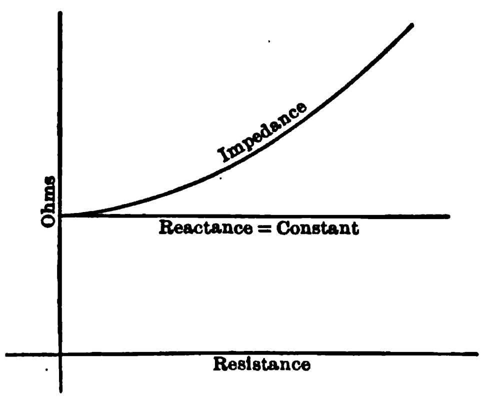

FIG. 110. Influence of variable resistance on the value of an impedance.

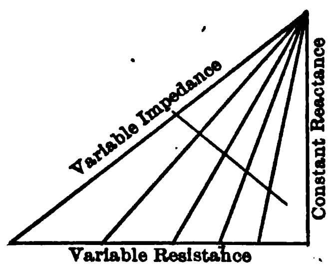

FIG. 111. Explanatory diagram to the curves shown in Fig. 110.

form a rectangular triangle, as in Fig. 108, so that any two of them check the third. Repeat this experiment with different values of current.

The influence of various factors on the impedance should now be investigated, as shown in Figs. 104 to 106. The two values to be measured are: The total impedance z and the ohmic resistance r. The reactance x is figured out either graphically, as in Fig. 108, or from the relation $x = \sqrt{z^2 - r^2}$. During this investigation the resistance r is kept constant. It will be noted that its influence becomes more pronounced, the smaller the reactance. It is also advisable to investigate the converse case (Fig. 110), the reactance being kept constant and the resistance gradually increased. It will be seen that the total impedance increases more slowly than the resistance. The geometrical reason for this may be seen from Fig. 111.

105. Triangle of Voltages. —It was shown in § 103 that a resistance and a reactance cannot be added arithmetically, but must be added geometrically at right angles; also that a drop of 40 volts across a reactance, and of 30 volts across a resistance in series with it, gives a total drop of only 50 volts, instead of 70 volts. This latter relation is deduced directly from Fig. 108, by multiplying the three sides of the triangle by the effective current i (Fig. 109). This gives a triangle of the effective values of voltage, across the resistance, across the reactance and across the total impedance. The triangle, Fig. 109, gives the same information in regard to the electrical relations in the circuit, as the set of sine waves in Fig. 102. The angle of lag ϕ is also represented in the triangle in its true magnitude. The diagram is completed by drawing a line which represents the current i. This line is in phase with the ohmic drop ir, since the two corresponding sine waves reach their maxima simultaneously.

Lines showing effective values and phase relation of alternating electrical quantities are called *vectors;* thus Fig. 109 is a vector diagram of currents and voltages in an inductive circuit. Such diagrams are now used almost exclusively in place of sine waves. They give the same information, and are much easier to read and to understand.

106. Phase Angle and Power Factor. —The phase angle ϕ, Fig. 109, is of great importance in determining the average power spent in a circuit. The actual power varies from moment to moment with the instantaneous values of current and voltage. When inductance is present, the power supplied becomes at times even negative; this is when the inductance gives back the stored electromagnetic energy (see §§ 96 and 97). For practical purposes only the average value of power, during one complete period of alternating current, is of importance.

If e is an instantaneous value of the voltage and i the corresponding value of the current, as in § 103, the average power during the time T of one cycle is

$$w = \frac{1}{T}\int_0^T ei\,dt.$$

Substituting the value e from the equation (6), we get

$$w = \frac{L}{T}\int_0^T idi + \frac{r}{T}\int_0^T i^2dt,$$

or

$$w = \frac{L}{T}\left(\frac{i^2}{2}\right)_0^T + ri^2_{eff}.$$

The first term on the right side is $= 0$ because i is the same for any two moments, differing by T. This shows that with periodically fluctuating currents, no power is permanently lost or gained in a reactance; it is merely stored part of each cycle and returned to the circuit during another part of the cycle. The power lost in the resistance is represented by the familiar expression ri^2_{eff}.

For circuits in which voltage and current vary according to sine law another expression for power is obtained by substituting E Cos ϕ in place of ir (Fig. 109). We find

$$w = E_{eff} \cdot i_{eff} \cdot \text{Cos}\,\phi \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

If the circuit is non-inductive Cos $\phi = 1$ and the power is represented by the product $E_{eff} \cdot i_{eff}$. This latter product is also called the apparent power. Cos ϕ is called the power factor, for it is the factor by which the apparent power must be multiplied in order to get the true power w. Another proof for the expression (13) will be found in § 75.

By having in the circuit an indicating wattmeter W (Fig. 107) true watts may be read directly in addition to the current and the voltages, and the power factor calculated from (13). Another way of determining Cos ϕ is from the triangle of voltages (Fig. 109). If the instruments are in calibration, the two methods yield the same result.

107. EXPERIMENT 5-D. —Power Relations with Resistance and Reactance in Series. — The purpose of the experiment is to make clear the relations deduced in §§ 105 and 106. The connections are shown in Fig. 107. A voltmeter switch T is used, by means of which the voltmeter may be made to indicate at will either the total voltage, the voltage across the inductance, or across the resistance. The connections to this switch are shown more in detail in Fig. 113. The resistance r_0 in Fig. 107 is meant to represent the small ohmic resistance unavoidable in the reactance coil x.

Select by trials such values of r and x as will give about the same drop across BC as across CD; read amperes, volts and watts. The voltmeter connection is shown to include the drop in the ammeter; this is advisable in order to have the same total voltage, as is impressed across the potential coil of the wattmeter. The resistance of the ammeter must thus be included in the value of r. Ohmic resistance is measured at the close of the experiment by the drop-of-potential method, using direct current. A double-throw switch D, shown in Fig. 113, is convenient for changing from alternating to direct current. Take several sets of readings, varying the applied voltage by the rheostat R. Repeat the same test with different values of r and x.

Report. (1) Plot amperes, watts and component volts to total volts as abscissæ (Fig. 112).

(2) Plot corrected values of pure resistance drop and pure reactance drop, as shown by dotted lines. This is done by adding ir_0 drop to

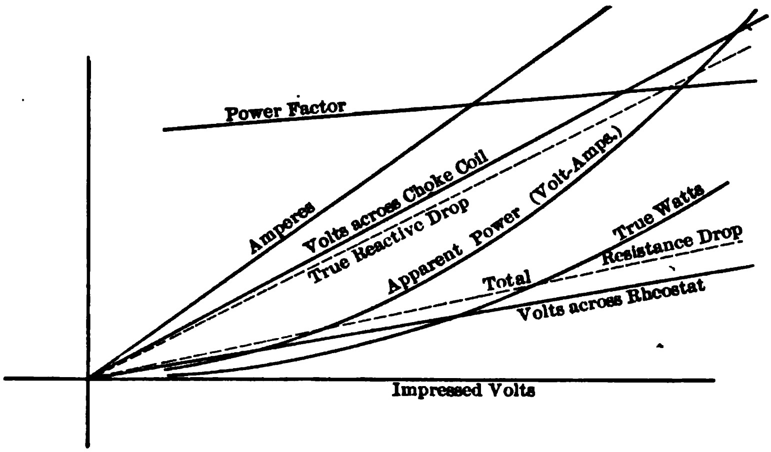

FIG. 112. Variations in amperes, watts, etc., consumed in the circuit shown in Fig. 107, with the change in impressed voltage.

ir and subtracting the total ohmic drop geometrically from the applied voltage.

(3) Show for a few points selected from the curves, that the power read on the wattmeter checks with the calculated expression $(r + r_0) \cdot i^2$.

(4) Check the values of Cos ϕ calculated as the ratio of true watts to apparent watts [expression (13)] with those determined from the triangle of voltages (Fig. 109).

108. Impedances in Series. —The relations deduced in §§ 103 to 107 may now be extended to the case of two or more resistances and reactances connected in series (Fig. 113). Such conditions are met in practice when, for instance, both the line and the current-consuming devices possess resistance and reactance, and it is desired to calculate the station e.m.f. and the power factor of the generator load.

The relations are shown in Fig. 114; the diagram is constructed for a given current i (horizontal vector). The total voltage drop across AC (Fig. 113) does not depend on the order in which the resistances and the reactances are connected. Therefore, we may substitute an equivalent resistance $R = r_1 + r_2$ for the two separate resistances r_1 and r_2. In a similar way an equivalent reactance $X = x_1 + x_2$ may be introduced. This gives th triangle APC analogous to that shown

in Fig. 108; AC is the combined, or equivalent impedance Z of the circuit. Multiplying Z by i, according to equation (12), the total

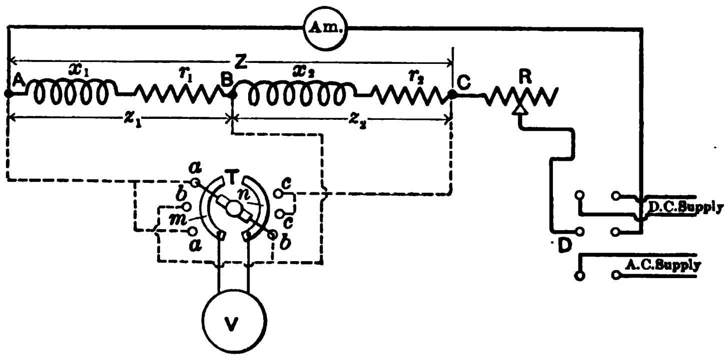

FIG. 113. Impedances in series.

voltage AC' is obtained. The triangle AMB shows the resistance, the inductance, and the impedance between the points A and B of the circuit; the triangle BNC gives the same values for the part of the

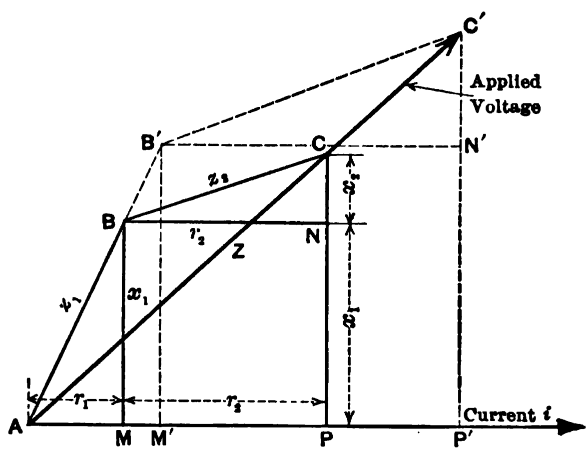

FIG. 114. Electrical relations with two impedances in series.

circuit between B and C. The triangle APC is a combination of these triangles. It may also be said, that the impedance Z is the geometric sum of the impedances z_1 and z_2.

By changing the scale of the diagram in the ratio of $AC' \div AC$ a diagram $AB'C'$ of component voltages is obtained, as shown by dotted

lines. AM' is the voltage across r_1; $M'P'$ is that across r_2. $M'B' = P'N'$ is the voltage across x_1 and $N'C'$ is that across x_2. The voltage across AB (Fig. 113) is represented by the vector AB'; the voltage across BC by $B'C'$. It may be said, that AC' is the geometric sum of AB' and $B'C'$. The angles of phase displacement between the current and the various voltages may also be measured on the diagram.

If the terminal voltage AC' is given instead of the current, the diagram is constructed on the basis of a current arbitrarily assumed; then the values obtained are reduced or increased in the ratio of the given voltage to that found by construction.

109. The Three-Voltmeter Method for Measuring Power.—A special case of the diagram shown in Fig. 114 is represented in Fig. 115. The reactance $x_1 = 0$, so that one of the impedances is reduced to a non-

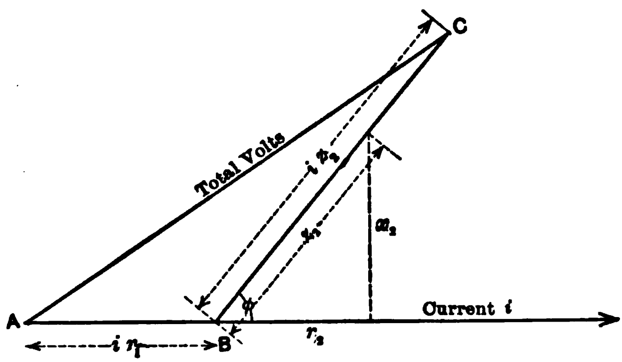

FIG. 115. Specific case of the diagrams shown in Figs. 113 and 114, when the reactance x_1 is zero.

inductive resistance r_1; in other respects both diagrams are identical. This case is of considerable practical importance, as the method can be used for determining power in an inductive circuit, without the use of a wattmeter. Let BC (Fig. 113) be an apparatus, such as a single-phase motor, and let it be necessary to determine watts power consumed in it, without using a wattmeter. According to equation (13), the power depends on the current, the voltage, and the phase displacement between the two. The current and the voltage are measured directly; the phase displacement may be determined from the diagram, Fig. 115.

For this purpose, a non-inductive resistance r_1 is connected in series with the apparatus BC; the three voltages AB, BC and AC (Fig. 115) are measured, as is the current i. The resistance r_1 being non-inductive, its drop AB is in phase with the current, so that the triangle ABC may

be constructed in its true phase relation to the current i. This gives the desired phase-angle ϕ at B. Projecting BC on i gives E Cos ϕ; this value being multiplied by i gives the required power.

If the value of r_2 is known, it is not necessary to have an ammeter, as the current can be calculated as the ratio, — voltage ÷ resistance.

This method is called *the three-voltmeter method*, because power, or at least the phase-angle, is determined from three voltmeter readings. It has been used to some extent in former years, but is now applied in exceptional cases only, since indicating wattmeters have come into universal use.

110. EXPERIMENT 5-E. — Voltage and Power Relations with Impedances in Series. — The connections are shown in Fig. 113, save that a wattmeter should be added as in Fig. 107. (a) Adjust the desired values of resistances and reactances, and take readings of

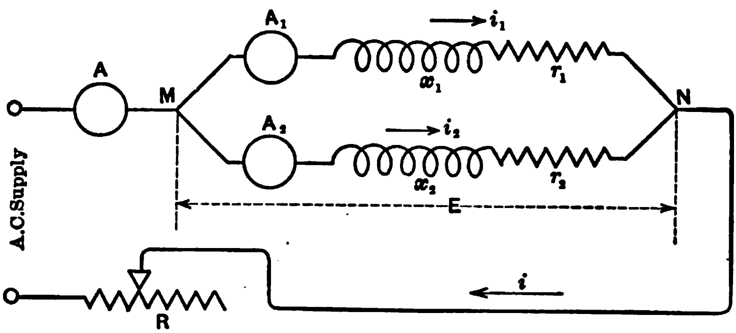

FIG. 116. Two impedances in parallel.

volts, amperes and watts. Read total watts, and watts across each impedance, separately. Gradually increase the applied voltage by regulating the resistance R; take similar readings with each setting of the rheostat. Put on direct current and measure the ohmic resistances by the drop-of-potential method. (b) Repeat the same experiment with different values of resistances and reactances. (c) For the same impedance determine the power consumed in it, first using a wattmeter, and then by the three-voltmeter method.

Report. Plot the results to total volts as abscissæ. Draw the diagram of voltages $AM'B'N'C'$ (Fig. 114) and check the cosines of the angles with those calculated from the wattmeter readings. Check the power determined by the three-voltmeter method with that read on the wattmeter, and with calculated i^2r.

111. Impedances in Parallel. —The connections are shown in Fig. 116. It is required to find the total line current i and its phase relation to the voltage E applied between M and N. Let us first consider

the simplest case, when one branch has a pure inductance x only; the other merely an ohmic resistance r (Fig. 117). The current in the first branch is $i_1 = E \div x$ and lags 90 degrees behind E; the current in the second branch is $i_2 = E \div r$, and is in phase with E. The total current i is the geometric sum of the two and is represented by the diagonal of the rectangle. Denoting the *equivalent* impedance of the circuit by z, we have:

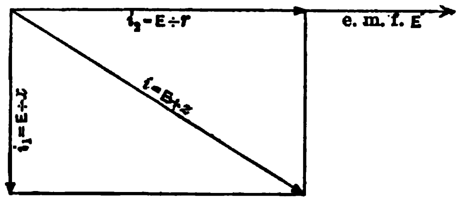

FIG. 117. Vector diagram of currents, with resistance and reactance connected in parallel.

$$\frac{1}{z} = \sqrt{\left(\frac{1}{x}\right)^2 + \left(\frac{1}{r}\right)^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

as distinguished from the expression (11), when a resistance and a reactance are connected in series.

When resistance and reactance are present in both parallel branches, the two component currents i_1 and i_2 are lagging behind the impressed e.m.f. OA (Fig. 118) by certain angles ϕ_1 and ϕ_2. The total current $i = OC$ is the geometric sum of the two and lags behind OA by the angle ϕ_0.

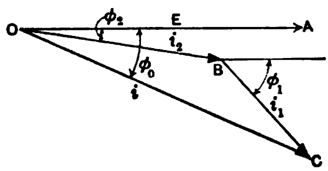

FIG. 118. Component currents and total current in the case of two impedances connected in parallel.

The same relations are shown in greater detail in Fig. 119. The applied voltage between the points M and N (Fig. 116) is represented by the vector OE. The voltages across the resistance and across the reactance in branch 1 are represented by the triangle OP_1E, as in Fig. 109. OP_1 is the drop in the resistance r_1; P_1E is that in the reactance x_1. The current i_1 being in phase with the ohmic drop is represented by a vector OC_1. The triangle OP_2E gives similar relations for the branch 2. If there are more branches in parallel, a triangle may be constructed for each branch. The apexes P_1, P_2, ... of all such triangles lie on a semicircle drawn on OE as a diameter. This is because all the triangles are rectangular, and all have OE for a hypothenuse. The total current i in the line is a geometrical sum of i_1 and i_2 and is represented by the vector OC. If there are more than two branches in parallel, the vectors of the component currents are added together as if they were mechanical forces radiating from the point O.

112. EXPERIMENT 5-F. — Study of Impedances in Parallel. — The purpose of the experiment is to illustrate the relations described in

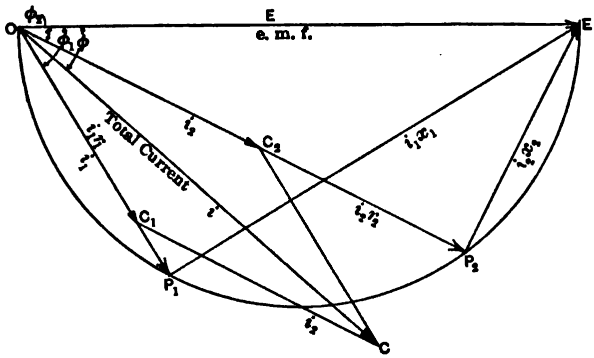

FIG. 119. Vector diagram of currents and voltages, corresponding to the connections in Fig. 116.

§ 111. The connections are shown in Fig. 120; they are identical with those in Fig. 116, except that one ammeter is used for all branches, being connected to a polyphase board (see § 49). A wattmeter is provided for determining phase relations. (a) Begin with the sim-

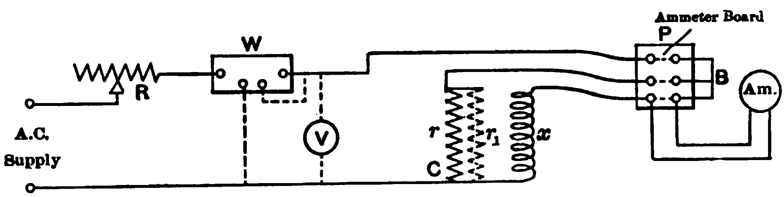

FIG. 120. Diagram of connections for investigating two impedances in parallel.

plest case, illustrated in Fig. 117, when one branch contains only inductance, the other only resistance. Measure the three currents, volts and watts. Gradually increase the voltage and take similar readings. Finally measure the resistance r with direct current. (b) Repeat a similar experiment with other values of resistance and reactance. (c) Take the more general case of r and x in both branches, as in Fig. 116. Read amperes, watts and volts; also component voltages in each branch.

Report. (1) Show that the three currents form a rectangular triangle, when pure resistance is connected in parallel with pure inductance; check the phase-angle ϕ with that determined by the wattmeter. Also show that the total power corresponds to i^2r in the resistance, and that no power is lost in the reactance.

(2) Draw several diagrams, as in Fig. 118, and show that the relations obtained from the volt and ampere readings check with those calculated from the wattmeter readings.

(3) Construct, for one set of readings, a complete diagram, as in Fig. 119.

NOTE. Resistance r_1, shown in Fig. 120, by dotted lines, is meant to represent the influence of the core loss in the reactance coil. A coil with iron loss in its core is electrically equivalent to an ideal coil with a high resistance shunted around it.

113. EXPERIMENT 5-G. — Motors and Lamps Connected in Parallel to the Same A. C. Supply. — This experiment is a practical illustration of the case discussed in §§ 111 and 112. The load in most power plants consists partly of incandescent lamps, which constitute a practically non-inductive load, and of induction motors having a lower power factor. The resultant load in the power house is the sum of the power taken by the lamps and of that taken by the motors; the resultant power factor lies somewhere between the average power factor of the motors, and 100 per cent.

In studying the electrical relations between inductive and non-inductive load it is *not necessary* to have the experiment arranged on a large scale, since the relations are the same at 5 amperes as they are at 5000 amperes. A laboratory experiment may be considered as representing the actual conditions when performed, for instance, on a ½ hp. motor and some 10 to 15 incandescent lamps connected in parallel with it. By multiplying the results, say by 1000, we get the relations taking place in a city having about 500 hp. in motors and from 10,000 to 15,000 incandescent lamps connected to the electric distributing system.

The load and the power factor vary in actual service in innumerable combinations. To make the problem more definite select two extreme cases: (1) All the lamps are turned on; motor load increases from zero to maximum. (2) All the motors are running at full load; the lamps are gradually turned on. The relations taking place in intermediate cases can be readily understood from the results of these two extreme conditions.

Connect the lamps and the motor in parallel to the power supply, as in Fig. 120, and arrange switches and instruments to read watts and amperes supplied to the lamps, to the motor, and to both. The voltage must be kept as nearly constant as possible during the whole experiment. Take two sets of readings, under the conditions described in (1) and (2) above.

Report. The results should be plotted to total watts as abscissæ; plot kw. lamp load, kw. motor load, lamp current, motor current, total current, resultant power factor and motor power factor; also calculate and plot wattless amperes. Two separate sets of curves should be plotted: one for constant motor load, the other for constant lamp load. The diagram, Fig. 118, is simplified in this case to that in Fig. 121 because the load in one of the branches is non-inductive. Check a few points of the above curves by means of this diagram. For instance, take the observed component currents, find from the diagram the total current and the resultant power factor, and compare them with the values directly observed. Or take the observed total current and one of its components, and determine from the diagram the other component current.

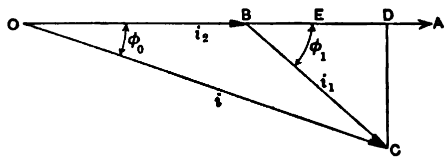

FIG. 121. Current relations when an inductive load and a non-inductive load are connected in parallel (specific case of Fig. 118).

114. Mutual Induction. — The reactance of a coil, such as C_1 (Fig. 122), is reduced by the proximity of another coil C_2, if the latter is

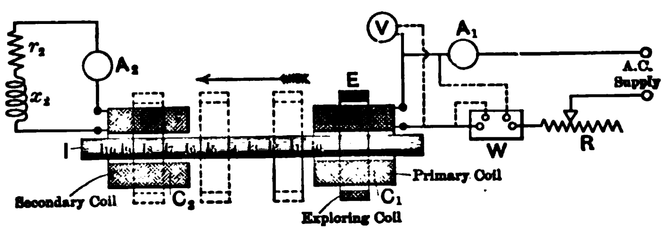

FIG. 122. Effect of mutual induction on the electrical relations in a circuit.

short-circuited upon itself. The reason is, that the flux produced by the first coil induces currents in the secondary coil. These currents oppose the action of the primary currents, reduce the flux, and consequently the counter-e.m.f. produced by the first coil.

The effect of the secondary coil depends, among other factors, upon its distance from the primary coil and on the character of the circuit on which it is closed (resistance r_2 and reactance x_2). The action is greatly intensified if both coils are mounted on an iron core, I. This interaction of two coils, without direct metallic connection, is called *mutual induction.*

In some practical cases, mutual induction is highly desirable; thus the action of transformers (Chapter XV) is based entirely upon it. In

other cases it has a harmful effect; for instance, when a power-transmission line parallels a telephone line, currents are induced, which interfere with the transmission of speech.

The electrical relations between two circuits having a mutual induction are usually too complicated to be expressed by practical formulæ or diagrams; it is merely desired that the student understand the physical character of the phenomenon, and the influence of the factors entering into it. This can be done as is explained in the following experiment.

115. EXPERIMENT 5-H. — Effect of Mutual Induction on the Reactance of a Circuit. — The phenomenon described in the preceding paragraph may be studied experimentally with apparatus as shown in Fig. 122. The coil C_1 under test is denoted the "Primary Coil." It is connected to an A. C. supply with an ammeter A_1, a voltmeter V, and a wattmeter W in the circuit, as usual. Another coil C_2 marked "Secondary Coil" is closed on a circuit consisting of a resistance r_2, reactance x_2 and an ammeter A_2. The secondary coil may be placed at any desired distance from the primary coil. In order to increase the inductive action between the two coils, they may both be put on a common iron core I. To investigate the influence of the position of the secondary coil, short-circuit it upon itself through the ammeter A_2, and bring it as close as possible to the primary coil (position "O"). Adjust the primary current by the resistance R to the maximum safe limit; read volts, amperes and watts. Gradually move C_2 away, keeping the primary volts constant. Take readings until the secondary coil is removed so far that its influence on the primary circuit is hardly noticeable. Finally open its circuit and again read the primary values.

As the coils are separated, the flux between them varies. The values of the flux can be ascertained by an exploring coil E connected to a separate voltmeter. The coil E is moved as shown by dotted lines, and the variations in the flux measured by the variations in the induced e.m.f. The voltmeter current is so small, that the presence of the exploring coil does not affect the electrical relations between the primary and the secondary coils.

Now investigate the influence of the character of the secondary circuit on the mutual inductance. Place the secondary coil at a short distance from the primary coil, and take several readings of volts, amperes and watts, varying the values of x_2 and r_2. Maintain either primary volts or primary amperes constant, in order to have a basis for comparison of results.

Report. Plot results to positions of the secondary coil as abscissæ

(Fig. 123). Plot the effect of varying secondary inductance and resistance; use as abscissæ the quantity which was varied. Give a physical explanation of the observed relations.

116. Measurement of Inductance with Wheatstone Bridge.— Small inductances, such as are used in telephone and telegraph work,

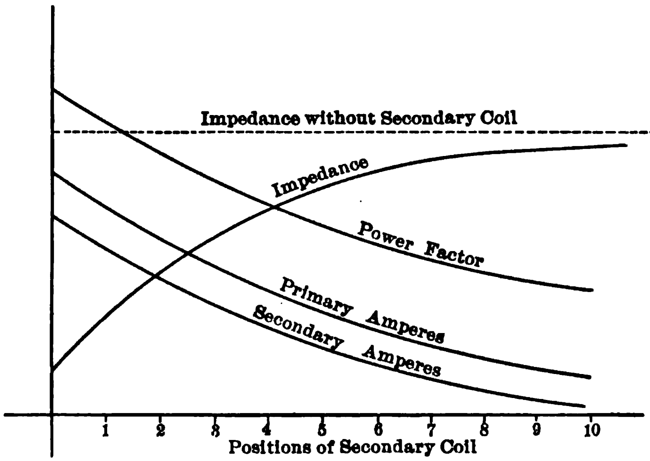

FIG. 123. Curves showing the effect of mutual induction, with the connections as per Fig. 122.

and in scientific research, are usually measured by means of a Wheatstone bridge, with direct or interrupted currents. The various methods employed may be found in physical-laboratory manuals and in textbooks on electricity and magnetism.

CHAPTER VI.

THE MAGNETIC CIRCUIT.

117. THE fundamental electromagnetic relations may be conveniently studied on the apparatus shown in Fig. 124. It consists of several sets of U-shaped pieces *m*, *m'*, of steel or iron and of magnetizing, or exciting coils *pp*, connected to a source of direct-current supply.

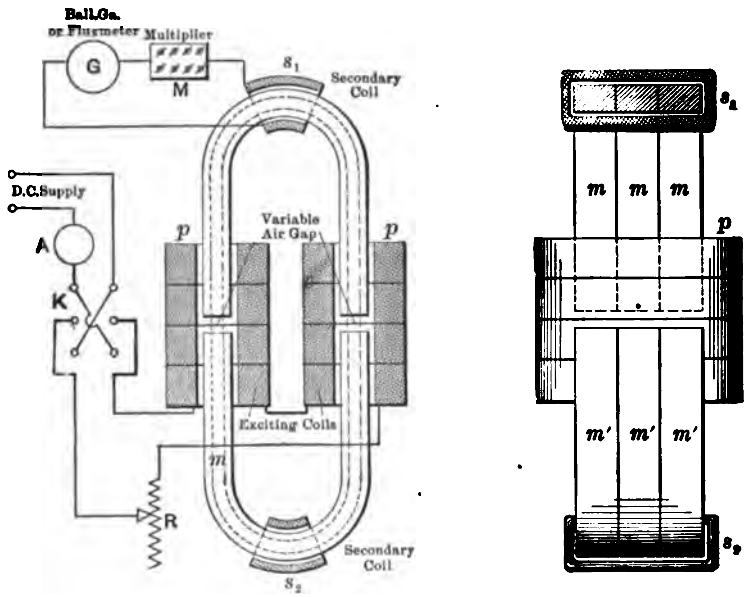

FIG. 124. An apparatus for studying the fundamental relations in a magnetic circuit.

K is a reversing switch by means of which the iron cores may be magnetized in either direction. When *K* is closed, a current flows through the coils *pp* and produces a magnetic flux, as shown by dotted lines. The intensity of magnetization — or the flux — may be varied:

(a) By regulating the exciting current with the rheostat *R*.

(b) By changing the number of coils in the circuit.

(c) By increasing or decreasing the air-gap between the upper and the lower cores.

(d) By changing the number of sections m, m'.

(e) By replacing the cores by others made of a better or of a poorer magnetic material.

The exciting current is read on the ammeter A. The amount of magnetism produced in the core is measured by the exploring coils s_1 and s_2, connected to a ballistic galvanometer (§ 119) or a fluxmeter (§ 120).

118. Ampere-Turns and Magnetic Flux. — The amount of magnetism produced in the cores m, m', depends on the magnitude of the exciting current, and on the number of turns in the exciting coils; but the magnetism remains constant so long as the product "current times turns" remains constant. For instance, a current of 5 amperes, flowing through a coil with 20 turns, produces the same magnetizing effect, as 20 amperes flowing through a coil having 5 turns, or 1 ampere with 100 turns. The magnetizing, or the *magnetomotive* force is the same in each case and is equal to 100 *ampere-turns*. The reason is easy to see. Imagine a current of 1 ampere flowing through 1 turn of wire, and take 100 such elements. Combine them in series and you get 1 ampere flowing through 100 turns; combining them in parallel gives 1 large turn with 100 amperes. The magnetic effect *outside* the coil cannot depend on whether the turns are connected in series or in parallel, but merely on the number of elements producing the action; therefore it depends on the number of ampere-turns only.

The magnetic state in a medium may be imagined as a state of tension or attraction along certain lines; these imaginary directions are called "magnetic lines" or "lines of force." They are shown in Fig. 124 by dotted lines. In this connection the reader may be reminded of the familiar physical experiment, in which iron filings arrange themselves around a steel magnet in certain directions; these are the directions of lines of force. Lines of force, apart from their direction, are purely imaginary; it is convenient, however, to measure magnetism by assigning a certain *numerical* value to each line of force. With this supposition, lines of force are considered closer to each other in places where magnetization is stronger, and vice versa. This leads to the conception of *density of lines of force,* so important in electrical engineering.

The sum total of lines of force within a certain space is called the magnetic flux. The usual way of measuring and defining the magnetic flux within a coil, such as the coil s_1 in Fig. 124, is by the electric effects produced by the flux. When the magnetic flux, passing through a coil, increases or decreases, an e.m.f. is induced in the coil, proportional to the rate of the variation of the flux. The rational unit of

magnetic flux in the volt-ampere-ohm system should therefore be based on the following definition: When a magnetic flux varies uniformly at the rate of one line of force per second, the e.m.f. induced in a coil which surrounds it is one volt per turn. Such a unit (called the *weber*) is too large for practical purposes; the unit actually used is based on a similar definition, except that a C. G. S. unit of electromotive force is taken instead of the volt. This unit is 10^8 times less than the volt; this coefficient enters therefore into all formulæ which express an induced e.m.f. in volts in terms of flux.

To make the above definition clearer, suppose that a certain magnetism is produced in the cores m, m' by exciting the coils p, p with a certain current. Let it be required to express this magnetism numerically by the number of lines of force. Let the secondary or exploring coil s_1 consist of 100 turns of wire and be connected to a very sensitive voltmeter. So long as the flux remains constant, the voltmeter shows no deflection. Let now the exciting current be gradually reduced to zero by the rheostat R, at such a rate, that the voltmeter shows all the time 0.05 volt. Suppose 30 seconds of time elapse before the current is reduced to zero and the flux disappears. From these data the original flux is figured out as follows: The e.m.f. induced in one turn of the secondary coil is, in C. G. S. units,

$$\frac{0.05 \times 10^8}{100} = 50{,}000 \text{ (C. G. S.)}$$

This, according to the above definition of the flux, shows that the flux was decreasing at the rate of 50,000 lines of force per second. As it took 30 seconds for the flux to be reduced to zero, the original flux was $50{,}000 \times 30 = 1{,}500{,}000$ lines of force.

In accordance with the modern fashion of naming magnetic and electric units after famous scientists, the unit of flux, or one line of force, as above defined, was named *the maxwell*, so that fluxes are expressed in maxwells. While the unit of flux defined on the basis of one volt per second is too large, the maxwell is too small a unit for many practical purposes. A compromise is reached by using the following derivative units:

1 kilo-maxwell (or kilo-line) = 1000 maxwells.

1 mega-maxwell (or mega-line) = 1,000,000 maxwells (= $\frac{1}{100}$ weber).

It would be rather troublesome to measure magnetic fluxes by gradually reducing them to zero at a rate to give a constant voltmeter deflection, as described above. The following two methods, though based on the same principle, are more convenient.

119. Measurement of Magnetic Flux with a Ballistic Galvanometer. — A ballistic galvanometer is a measuring instrument whose deflections are proportional to very brief electric discharges through it. An electric discharge through such a galvanometer may be made proportional to a sudden change in a magnetic flux. For this reason the ballistic galvanometer is widely used for measuring magnetic fluxes. Like most galvanometers, so widely used in physics, a ballistic galvanometer (Fig. 126) consists of a coil of fine wire suspended in the field of a permanent magnet. When a current passes through the coil, it is deflected according to the strength of the current. The torsion of suspension wires, or spiral springs (Fig. 34) return the coil to zero, when no current flows.

The only difference between the usual type and the ballistic galvanometer is, that the moving part of the latter has a much greater inertia. This is necessary in order that the coil should not begin to move, until the total discharge has passed through it. Only under this condition does the instrument give deflections, which depend on total discharge, rather than on its duration or the instantaneous values of the current. If, for instance, the moving part is made so heavy, that the period of its swing is 10 seconds, the coil will not move appreciably with any discharge that lasts, say, less than 0.5 second.

For measuring a magnetic flux, the ballistic galvanometer is connected to the secondary coil s_1, — if necessary through a resistance M to reduce deflections. As long as the flux remains constant, the galvanometer shows zero, but if the flux is suddenly changed, an electric discharge is induced in the galvanometer circuit, and the coil begins to move. The final deflection multiplied by a constant of the instrument is a measure for the change in flux. Let, for instance, the galvanometer constant be 50,000 maxwells per 1 cm. scale deflection. Then should the deflection be 15 cm., the change in flux is $50{,}000 \times 15 = 750{,}000$ maxwells, or 750 kilo-lines.

The theory and the calibration of ballistic galvanometers are explained in §§ 157 and 158.

120. Grassot Fluxmeter. — The disadvantages of the ballistic galvanometer, described in the preceding article, are:

(1) It is necessary to change the flux in order to measure it.

(2) The change must be sudden, in order that the electric discharge be completed before the galvanometer coil begins to move.

(3) The indications are only instantaneous, as the moving coil immediately begins to return.

These disadvantages are eliminated in the Grassot fluxmeter, shown

in Fig. 125. The details of the moving part are shown in Fig. 126. It is essentially a ballistic galvanometer, except that the moving coil is suspended from a single cocoon fiber of negligible torsional stiffness. In an ordinary ballistic galvanometer the coil is returned to zero under the influence of the torsion of the suspension wire; while in the fluxmeter the coil remains at rest in any position, and creeps only excessively slowly towards zero. The upper end of the fiber is attached to the flat spiral spring R to minimize the effect of shocks. The stiff wire frame E fixed upon the coil B allows of a central attachment of the very thin silver strips s and s', serving to lead the current to and from the coil B. The soft iron core A is supported within the coil, between the pole-pieces NS of a permanent magnet, the field in the air-gap being of a great and uniform intensity. An arrestment, controlled by a milled button in front of the instrument, serves to lock the coil when not in use; at the same time it brings the pointer back to zero.

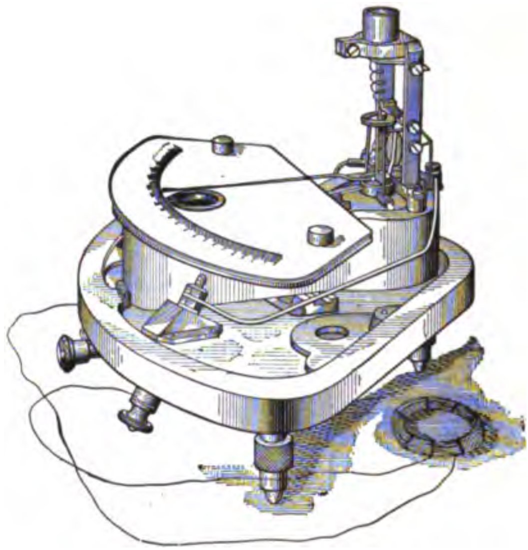

FIG. 125. The Grassot fluxmeter.

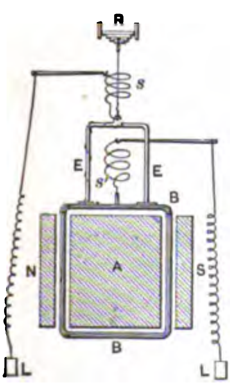

FIG. 126. Arrangement of parts in the Grassot fluxmeter.

The instrument is connected as shown in Fig. 124. When the switch K is closed, the coil of the fluxmeter starts into motion and comes to rest in a new position, the deflection being determined solely by the magnitude of the flux (§ 157 b). Whether the flux is increased suddenly or gradually, the deflection is precisely the same. When the flux is varied, the needle of the instrument follows the variations. When the exciting circuit is opened, the coil returns once more to its zero position. The fluxmeter may be calibrated directly in maxwells; it permits the reading of magnetic fluxes with the same facility with

which currents and voltages are read on ordinary ammeters and voltmeters.

121. Saturation in Iron. — Experience shows, that magnetic flux in air and in other non-magnetic substances is strictly proportional to the number of ampere-turns which produce it. On the contrary, in iron and steel the flux, while intensified many times, increases more slowly than the exciting ampere-turns (Fig. 127). This peculiar property of iron is expressed, for the lack of a better term, by saying that the iron becomes gradually *saturated* with lines of force, and only reluctantly allows their number to be increased. The following example may make this clearer.

Let the iron cores in the apparatus, shown in Fig. 124, be removed, and a current of 10 amperes sent through the exciting coils. Let the fluxmeter register a small flux of 2 kilo-lines (in the air). With an exciting current of 20 amperes it will register 4 kilo-lines. Now put the cores in place and excite the coils again with 10 amperes; a much larger flux will be found, say 800 kilo-lines. But at 20 amperes the flux will probably be only 1200 instead of 1600 kilo-lines, showing that the iron is approaching the saturation limit. The influence of saturation is seen by the curves (Fig. 127) gradually bending toward the axis of abscissæ; for a given per cent increase in excitation, the flux increase becomes less and less.

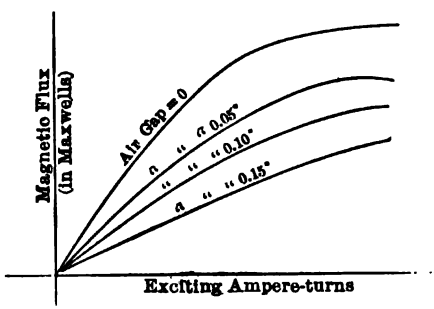

FIG. 127. Influence of small air-gaps on the magnetic flux.

The curves in Fig. 127 illustrate clearly the difference in the magnetic properties of air and iron. The addition of a very small air-gap — a few thousandths of an inch — decreases appreciably the flux produced by a given number of ampere-turns. This is expressed by saying that the *permeability* of air is much lower than that of iron.

For some practical purposes it is desirable to express the degree of saturation numerically. The revised Standardization Rules (1907) of the American Institute of Electrical Engineers specify the so-called *saturation factor* as a criterion of the degree of saturation, attained in a magnetic circuit. The saturation factor, by definition, is the ratio of a certain (small) per cent increase in exciting ampere-turns to the corresponding percentage increase in magnetic flux thereby produced. In the lower part of the curve (Fig. 127) one per cent increase in excit-

ing ampere-turns produces one per cent increase in the flux; therefore, the saturation factor here is unity. As the curve bends towards the axis of abscissæ the saturation factor gradually increases to infinity. The reciprocal of the saturation factor, deducted from unity, is called *percentage of saturation*. For a graphical method of determination of the saturation factor and of the percentage of saturation see Articles 57 and 58 of the *Standardization Rules*.

122. EXPERIMENT 6-A. — Magnetization Curves and Influence of Air-Gap. — The purpose of the experiment is to illustrate the fundamental relations between a magnetic flux and its exciting ampere-turns. The connections are shown in Fig. 124. The constant of the ballistic galvanometer or of the fluxmeter is supposed to be known; otherwise the instrument is calibrated as described in § 158. Before beginning the experiment, thoroughly demagnetize the cores from the residual flux which they may contain after a previous experiment. To do this, excite the cores to a considerable degree and then gradually reduce the current to zero by the rheostat R, at the same time continually reversing the current by the switch K.

Eliminate the air-gap as thoroughly as possible, by bringing the cores together, and excite the circuit with a small current, keeping the galvanometer circuit open.

(a) With the circuit of the galvanometer closed, but with the coil at rest, read the exciting current and suddenly reverse K; observe the galvanometer deflection. It is preferable in practice to reverse the exciting current, instead of opening the circuit, on account of some indefinite residual magnetism which remains when the circuit is opened. By reversing the current the flux is changed by a definite amount $N - (-N) = 2N$. Again open the galvanometer circuit, increase the exciting current, and produce a second discharge through the galvanometer by reversing the switch K. Proceed in this way as far as the exciting coils will stand the increasing current. To keep galvanometer deflections within reasonable limits either the resistance M is varied, or the number of turns in the coil s_1.

(b) Again demagnetize the cores and repeat the same experiment with a definite air-gap, say 0.010 inch. Such an air-gap may be easily obtained by interposing a thin piece of fiber or paper between the cores; these materials being non-magnetic have the same effect as so much air. Take a magnetization curve as before. Make similar tests with larger air-gaps.

(c) Substitute cores made of other kinds of magnetic materials, say wrought iron, and cast iron.

(d) Check the statement made in § 118, that the exciting force

depends on the number of ampere-turns, and not on the number of turns and the current separately.

If a fluxmeter is used instead of a ballistic galvanometer it is not necessary to reverse the exciting current. After the cores have been demagnetized, connect the fluxmeter to the secondary coil s_1, and gradually increase the magnetizing current. Read exciting amperes and fluxmeter deflections.

Report. (1) Plot curves as in Fig. 127.

(2) Plot values of saturation factor (§ 121) for an upper and a lower curve.

(3) Plot curves of ampere-turns necessary for the air-gaps alone, by subtracting from the total ampere-turns the excitation required for the iron parts of the circuit.

(4) Show from the curves above that the air-gap ampere-turns are proportional to the length of the gap and to the flux density.

123. Influence of the Length and Cross-Section of a Magnetic Circuit on its Reluctance. — Imagine the magnetic circuit, shown in Fig. 124, to be entirely closed, that is to say, to consist of a solid piece of iron without any air-gap. Experience shows that in this case the number of ampere-turns necessary to produce a given flux is proportional to the length of the magnetic circuit; this length is the average length of the lines of force, as indicated by the dotted lines. This fact is analogous to a similar relation in the electrical circuit, namely, that the e.m.f. necessary to produce a certain current in a conductor is proportional to the length of the conductor, other conditions being identical. Here the exciting ampere-turns, or the magnetomotive force, is analogous to electromotive force, and the magnetic flux to electric current. The magnetic circuit may thus be said to possess a certain resistance to the passage of lines of force. To distinguish this magnetic resistance from electrical resistance, the former is called "reluctance." Thus we may say that reluctance is proportional to the length of a uniform magnetic circuit.

Experience shows, also, that with non-magnetic materials reluctance is inversely proportional to the cross-section of the path of the flux. This is again analogous to electrical resistance, which is inversely proportional to the cross-section of a conductor. The rule is not altogether true for steel and iron, on account of the peculiar phenomenon of saturation described in § 121 (unless referred to a constant flux density). When the number of lines of force per square inch, or the magnetic density, increases, the required number of ampere-turns increases more rapidly than the flux. This is equivalent to saying that the permeability (magnetic conductivity) of iron decreases as the flux density increases.

124. Flux Density and Ampere-Turns per Inch. — The above considerations show that the number of ampere-turns per unit length, necessary for producing a given flux, in a given uniform magnetic circuit, is proportional to the length of the circuit, and depends on the magnetic density, but not on the value of the flux itself.* Thus, the necessary number of ampere-turns may be expressed with the aid of a single experimental coefficient: *Ampere-turns per unit length at a given flux density.* In the above example (§ 121) let the cross-section of the iron be 10 square inches, so that the flux density with 10 amperes exciting current is 80 kilo-lines per square inch. Let the number of

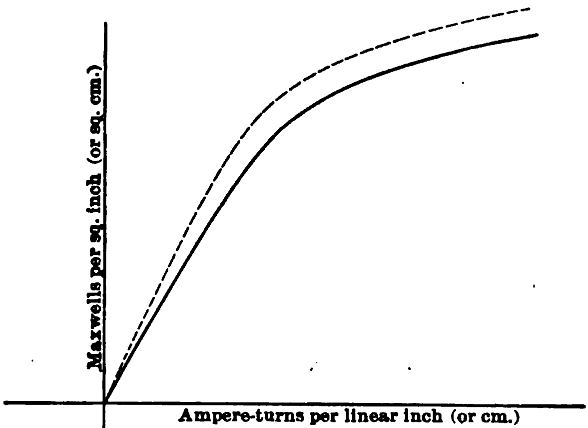

FIG. 128. Magnetization curve of a sample of iron, and the influence of an imperfect magnetic contact (the dotted line represents the ideal curve).

turns in the exciting coils be 320, and the length of the magnetic circuit 100 inches. Then, with the iron used,

$$\frac{320 \times 10}{100} = 32 \text{ ampere-turns per linear inch}$$

necessary to produce the above flux density. This number, 32, characterizes the material at the density of 80 kilo-lines, without regard to the length or the cross-section of the circuit. The curve shown in Fig. 128 is plotted in this way from the upper curve in Fig. 127. The

* The magnetic circuit is no different in this respect from the electric circuit. The familiar Ohm's law may be written in the form

$$E = I \cdot k \frac{l}{q}$$

or

$$\frac{E}{l} = k \frac{I}{q}$$

which means, that the e.m.f. per unit length of conductor is proportional to current density, but does not depend on the value of the current itself.

dotted curve shows the ideal case when the cores consist of one solid piece of iron; the curve below it is the one obtained with the arrangement shown in Fig. 124, where a small air-gap is unavoidable.

125. EXPERIMENT 6-D. — Influence of the Length and Cross-Section of a Magnetic Circuit on its Reluctance. — The arrangement of apparatus and the method for measuring the flux is the same as in § 122. (a) Take one section of the cores m, m' (Fig. 124) and bring the ends together as accurately as possible, so as to reduce the air-gap to a minimum. Take a magnetization curve, as in Fig. 127. (b) Now take the cores apart and fasten between them two straight pieces of iron, of the same cross-section and same quality of material as the rest, so as to increase the length of the magnetic circuit. Taking a similar curve, you will find that more ampere-turns are necessary to produce the same flux, because of the greater length of the magnetic circuit. (c) Take out the straight pieces and add more sections m, m' in parallel, so as to increase the cross-section of the magnetic circuit. Again take a magnetization curve. It will be found that the same flux is obtained with a considerably smaller number of ampere-turns. (d) Repeat the same experiment with cores made of different material.

Report. Show from the results of the test that the number of ampere-turns necessary to produce a given flux is proportional to the length of the circuit, but increases faster than the decrease in the cross-section of the magnetic circuit, due to saturation in the iron. For each material tested plot a curve, as in Fig. 128.

126. Magnetic Leakage. — When two or more paths in parallel are offered to an electric current, it is divided into parts inversely proportional to the resistances of the paths. In a similar way, a magnetic flux is divided when two paths are offered to it, as in Fig. 129. The apparatus shown there is the same as in Fig. 124, only the exciting coils pp are placed unsymmetrically. The flux produced in the lower core in part goes through the upper core, in part finds its way directly through the air, as shown by dotted lines. This latter portion is called the *leakage flux*, because in most practical cases it is not utilized for the purpose for which the magnetic circuit is produced. Thus, in electric generators and motors, part of the flux — instead of going through the armature of the machine — is shunted around it, and passes uselessly from pole to pole, directly through the air. The lower core in Fig. 129 corresponds to the field frame of a machine, the upper one to its armature.

The harm occasioned by magnetic leakage consists in the necessity for a larger flux to be produced than is actually utilized. This means

more exciting ampere-turns, consequently more copper, and more expenditure of energy for excitation. The case is made worse by saturation in iron, since any increase in flux means a disproportional increase in the number of exciting ampere-turns. Suppose, for instance, that the leakage in a certain case amounts to 20 per cent of the useful flux (this is not an uncommon figure in practice). The increase in the exciting ampere-turns necessary for producing 20 per cent additional lines of force may be 50 per cent or more, due to a higher saturation in iron.

For this reason it is of importance to know how to measure magnetic leakage, and to learn the principal factors upon which it depends. In the apparatus shown in Fig. 129, the leakage flux, or the difference between the total and the useful fluxes, may be measured by a ballistic galvanometer or a fluxmeter as before, by taking discharges first through the coil s_2 (total flux), then through s_1 (useful flux). It is more difficult to study accurately the actual distribution of the leakage flux in space, because this means measuring its magnitude and direction from point to point. At the same time, a study of the map of magnetic leakage is of a considerable practical importance, because it permits the designer to modify the form and dimensions of the frame of a machine so as to minimize the leakage.

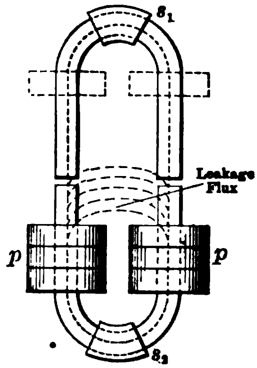

FIG. 129. Arrangement of coils for studying magnetic leakage with the apparatus illustrated in Fig. 124.

A preliminary study of distribution of the leakage flux may be made with a small magnetic needle freely suspended from a silk thread. The direction of the needle in different places of the stray field gives an idea as to the directions of the leakage lines of force. After this, the flux may be investigated either with a ballistic galvanometer, a fluxmeter, or a bismuth spiral (§ 165). When a ballistic galvanometer is used, a small exploring coil is connected to it, and is brought into the place in which it is desired to measure the leakage. The coil is held on a pivot by a retaining spring. Relieving the spring, the coil is snapped by 180 degrees. The flux cut during this movement produces a discharge in the galvanometer proportional to the flux. If this is impracticable, for instance, because of a narrow space, the coil is made flat and after having been brought into the desired place is withdrawn quickly from the field. In some other cases the exciting current must be broken or reversed in order to produce the desired galvanometer deflection.

When using a fluxmeter or a bismuth spiral, the mere fact of bringing the exploring coil into the field gives the desired deflection.

127. Factors on which Magnetic Leakage Depends. — Generally speaking, the magnitude of a leakage flux depends on the relative values of the reluctances of the useful path and of the stray paths. Any factor which decreases the reluctance of the stray path or increases the reluctance of the useful path creates conditions favorable for leakage. Thus, for instance, making the U-shaped cores (Fig. 129) narrower, in other words, bringing the two legs of each core closer together, is sure to increase the leakage, as it shortens the path for the leakage flux through the air. Increasing the air-gap between the two U's also increases per cent leakage, because it increases the reluctance of the useful path. For the same reason per cent leakage increases with the increase in saturation in iron. Moving the exciting coils lower, increases the cross-section of the leakage flux (in the vertical plane perpendicular to the paper), consequently increases the leakage flux itself.

An important case of increase in leakage is that due to some counteracting ampere-turns (here put on the upper core, as shown by dotted lines). This corresponds in practice to armature currents which counteract the excitation produced by the field coils. The phenomenon is known in generators and motors as *the armature reaction.* That armature reaction increases magnetic leakage, may be understood from the following example. Let it be required to maintain a certain flux of N lines of force in the upper core (Fig. 129), whether or not a current flows through the upper coils shown by dotted lines. Suppose that each section of the coils has 40 turns, and that at no load the necessary flux N is produced with 10 amperes exciting current, or $10 \times 6 \times 40 = 2400$ ampere-turns. Let the leakage flux at no load be 20 per cent of N. Now suppose that an opposing current of 15 amperes is sent through the upper coils, creating an armature reaction of $15 \times 2 \times 40 = 1200$ ampere-turns. Without leakage, the lower exciting coils would have to produce $2400 + 1200 = 3600$ ampere-turns in order to give the same flux as before. With leakage this increase is not sufficient, as is shown by the following simple calculation. The leakage flux in the lower core at no load was $0.2\ N$; the increase in ampere-turns to 3600 increases the leakage to

$$0.2\,N \times \frac{3600}{2400} = 0.3\,N.$$

Consequently, with the same total flux $1.2\ N$ as before, the flux in the upper core is now only $1.2\ N - 0.3\ N = 0.9\ N$, even though 50 per cent increase in ampere-turns were added on the lower core. This shows the importance of keeping the magnetic leakage as low as possible.

128. EXPERIMENT 6-C. — A Study of Magnetic Leakage. — The purpose of the experiment is to illustrate the relations explained in the two preceding articles. The apparatus used is shown in Figs. 124 and 129. Magnetic leakage depends on several factors, and it is best to investigate the influence of each factor separately. The total flux is measured by discharge through the coil s_2 (Fig. 129), the useful flux by that through the coil s_1.

(*a*) *Influence of air-gap and of saturation.* Set the exciting coils *pp* as shown in Fig. 129, and place the upper core as close as possible to the lower core (no air-gap). Take an accurate curve of fluxes in s_1 and s_2 with various values of the exciting current (Fig. 127). Read

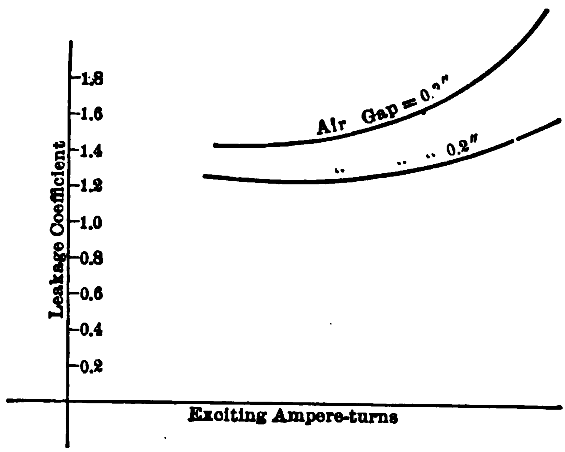

FIG. 130. Increase in per cent leakage with increased saturation in iron.

the fluxes as in experiment 7-A (§ 122). Repeat similar tests with two or three different values of air-gap.

(*b*) *Influence of the position of the magnetizing coils.* Select a value of air-gap, place the exciting coils symmetrically with respect to the two cores, as in Fig. 124, and measure the fluxes in both cores. Then gradually move the coils lower, as in Fig. 129, and take similar readings. Repeat the same experiment with different values of air-gap and of the exciting current.

(*c*) *Influence of the shape of pole-pieces.* Put pieces of iron on the inner side of the ends of the lower core, so as to assist the leakage through the air. Investigate the influence of the shape of these pole-pieces with different degrees of saturation in the iron and with different lengths of the air-gap.

(*d*) *Effect of armature reaction.* Excite the coils on the upper core to oppose the lower coils, as shown in Fig. 129. Determine the value of the flux in s_2 necessary for producing a given flux in s_1, with and without the opposing coils. Reverse the current in the upper coils, so as to make them assist the lower exciting coils; observe the change in leakage. Repeat similar tests with different positions of the coils, different degrees of saturation in the iron and various lengths of air-gap.

Report the results in such a form as to make clear the influence of each factor. The ratio of total flux to useful flux is called *the leakage coefficient.* Make use of this coefficient in order to bring out the results of the experiment in a simple form. Sample curves showing the effect of air-gap and of saturation on the value of this coefficient are given in Fig. 130.

129. EXPERIMENT 6-D. — Maps of Stray Flux. — This experiment supplements the preceding one, the purpose being to determine the actual paths of leakage lines of force. The methods of observation are described in § 126. Establish certain magnetic conditions, as in Fig. 152, and investigate as closely as possible the direction and the magnitude of the stray flux at various places. Change the conditions, as indicated in the preceding experiment, and see the effect on the stray flux. Preferably select the same conditions for which values of the leakage coefficient were determined in the preceding experiment.

Report. Plot the principal directions of the stray flux in several vertical and horizontal planes; mark the magnetic densities per square inch or square cm. State whether the densities at all points increase proportionately with the increase in current. Discuss the influence of the factors enumerated in § 128, and show how they should theoretically affect the distribution and the intensity of the stray flux.

MAGNETIC FIELD OF DIRECT-CURRENT MACHINES.

130. The fundamental properties of the magnetic circuit investigated above will now be applied to a study of magnetic fields in electric generators and motors. In laying out a machine, the designer makes certain assumptions by which he determines the value and the distribution of the magnetic flux in the machine. A knowledge of the experimental methods by which the magnetic quantities are measured on actual machines is of primary importance, since the test data serve as a foundation for design. The principal values of importance are:

(1) Total flux in the armature and field (Fig. 192).

(2) Leakage coefficient, or the ratio between the total and the useful flux (§ 128).

(3) Distribution of the flux in the air-gap (Fig. 131). These three points will now be taken up more in detail.

131. Total Flux in Armature and Field.—Magnetic flux in the armature of a machine is smaller than that in the field, since part of the flux finds its way from pole to pole through the air surrounding the armature, constituting what is called the leakage or the stray flux (Fig. 129). Both fluxes may be measured by a calibrated ballistic galvanometer, as in Fig. 124. To measure the flux in a pole-piece a known number of turns of an exploring winding are wound on the pole and connected to the ballistic galvanometer. A current is sent through the regular field winding, and then the circuit is opened, or, still better, reversed (to eliminate residual magnetism). Knowing the ballistic constant, the flux can be figured out directly in maxwells from the instrument reading. A fluxmeter (§ 120) may be conveniently used instead of the ballistic galvanometer.

It is hardly practicable with large machines to suddenly open the field circuit, or to reverse the current, on account of the very high self-induction of the windings. The induced e.m.f.'s may reach several thousand volts, are dangerous to the operator, and harmful to the insulation of the winding. In such cases the flux is varied in steps. A resistance is connected in series with the field winding, and is short-circuited by a switch. By suddenly opening the switch the flux is changed, due to the decrease of field current, and the ballistic impulse (often called kick) may be observed. If a fluxmeter is available, the field may be varied slowly, and a total magnetization curve taken in a very few minutes.

The flux in the armature is measured by putting on it an exploring winding, which embraces the useful flux passing from one pole to the next through the armature iron. The exploring coil is connected to the ballistic galvanometer as before and impulses produced by varying the field current. Another simple method for determining the total flux in the armature is to drive the machine at no load, and to calculate the flux from the induced e.m.f. by the familiar formula

$$E = \frac{\Phi \times n \times (\text{r.p.m.})}{60} \times 10^{-8}.$$

n is the total number of conductors on the armature, and Φ the useful flux (per pole) of the machine, in maxwells. The formula is applicable to bipolar machines and such multipolar armatures as are multiple-wound (see § 639). For series-wound multipolar armatures

$$E = p\frac{\Phi \times n \times (\text{r.p.m.})}{60} \times 10^{-8},$$

where p is the number of pairs of poles.

When the value of the leakage coefficient of the machine is known, the corresponding flux in the pole-pieces can be calculated, or at least estimated.

One of the most important problems in connection with flux calculations is that of estimating the influence of armature reaction, or the armature demagnetizing ampere-turns. This influence may be determined experimentally by sending a current through the armature from an outside source; the armature must be clamped so that it cannot revolve. The flux existing in the field with various currents in the armature, and different settings of brushes, is measured as before. With the brushes set on one side of the neutral, the field is weakened by the armature reaction; on the other side it is strengthened.

132. EXPERIMENT 6-E. — Measurement of Magnetic Flux in D. C. Machines. — A calibrated ballistic galvanometer (§ 119) or a flux meter (§ 120) must be provided for the purpose. Put a certain number of turns of fine wire on one of the field coils and the same number of turns on the armature. Begin the experiment with the field at zero value, having previously demagnetized the iron (§ 122). Increase the flux in steps, observing each time the ballistic throw. It is best to go over the complete cycle several times to be sure that the deflections are correct. Make similar runs with the ballistic galvanometer connected to the exploring coil on the armature.

After this, investigate the influence of the armature reaction. Clamp the armature, so that it cannot revolve; set the brushes on the neutral. Send a comparatively large current through the armature, and take the same magnetization cycles as before. This part of the experiment can be much more conveniently performed with a fluxmeter than with a ballistic galvanometer. Shift the brushes by one commutator segment, and repeat the same run, shift the brushes again, etc. Carry this operation as far as the brush-holder can be moved. Make similar runs with the brushes shifted in the opposite direction.

If possible, perform this test on a machine provided with compensating poles (§ 262), in order to see the influence of the compensating winding.

If the number of turns in the armature winding and the connections are known, take a no-load saturation curve (Fig. 194) in order to check the values of the flux by the formula given in § 131. Or, this method may be applied for determining the constant of the ballistic galvanometer.

Report. Plot to exciting current as abscissæ, values of flux in the pole-pieces and in the armature; plot to the same abscissæ the ratio of

the fluxes, or the leakage coefficient of the machine (>1). Check the values of the armature flux obtained ballistically with those calculated from the induced e.m.f. Plot to brush positions as abscissæ values of flux as influenced by the armature reaction; draw on the same sheet a horizontal line showing the flux with the armature circuit open. Explain the cause of the demagnetizing action of the armature, and the influence of the position of the brushes.

133. Leakage Coefficient. — The leakage coefficient, by definition, is the ratio of the total flux produced in a pole to the flux actually used in the armature for inducing e.m.f.'s. This ratio varies in modern machines from 1.20 to 1.50, according to the type, proportions, and saturation in the iron. A leakage coefficient of 1.30 means that out of every 130 lines of force produced in pole-pieces, only 100 actually pass into the armature; the rest find their path directly through the air from pole to pole.

It is important to keep the leakage flux as low as possible, since any increase in flux means a disproportionate increase in field copper, on account of saturation of the iron (§ 127). Moreover, machines with large leakage give a poor voltage regulation, because the armature reaction more easily deflects the flux into leakage paths. The leakage coefficient increases with saturation, because of the increase in the reluctance of the useful path in the armature, while that of the leakage paths in the air remains constant.

With the same useful flux, the leakage is larger when the machine is loaded than at no load, because the magnetomotive force between the poles is larger (§ 127).

The leakage coefficient may be determined as explained in § 132 by measuring ballistically the fluxes in the field and the armature and taking their ratio. The galvanometer does not need to be calibrated; the ratio of deflections gives directly the value of the leakage coefficient.

Mr. R. Goldschmidt suggested a compensation (or zero) method which does not require a ballistic galvanometer. According to this method a smaller number of exploring turns is put on the pole-piece than on the armature; the two exploring coils are connected in opposition, and in series with an ordinary low-reading voltmeter (in place of a ballistic galvanometer). When the flux is varied, the impulses induced in the two coils are in opposite directions, and the voltmeter receives the difference of the two. The ratio of the number of turns in the two coils is varied until the voltmeter needle remains at zero — when the flux is increased or decreased. Then the inverse ratio of the number of turns gives the ratio of the fluxes, or the leakage coefficient.

Suppose, for instance, that 20 turns were put on the armature. With 15 turns on the field, the voltmeter gave a small deflection in one direction; with 16 turns, in the opposite direction. The ratio of the fluxes, or the leakage coefficient, is between

$$\frac{20}{15} = 1.33 \text{ and } \frac{20}{16} = 1.25.$$

The true value may be estimated by noting the relative values of the deflections. This method is not as accurate as the ballistic method, but is accurate enough for technical purposes, and more convenient for testing floor work.

When using Goldschmidt's method the moving system of the voltmeter must be slightly weighted, so as to increase its moment of inertia. Otherwise the pointer moves both ways while the flux is being changed. This is because the flux often does not vary at the same rate in the field and in the armature.

In some cases, especially with new designs, it is desired to know not only the value of the leakage coefficient, but also the actual distribution of the leakage flux. This enables the designer to find where most of the flux is lost and to change the forms and the proportions. The methods for exploring the stray flux are described in §§ 126 and 129.

134. EXPERIMENT 6-F. — Determination of Magnetic Leakage Coefficient in Electrical Machines. — The arrangement of the apparatus is the same as in § 132; in fact, the two experiments may be performed simultaneously. Investigate the influence of the factors mentioned in § 133. At the end of the experiment increase the pole arcs by adding strips of iron on both sides of the pole-pieces; observe the resultant increase in leakage. It is not necessary to fasten the strips; they will be securely held in place by magnetic attraction. Try Goldschmidt's method of measuring the leakage coefficient with an ordinary voltmeter.

Report. Plot to exciting currents as abscissæ, values of leakage coefficient with no current in the armature. Plot to brush positions as abscissæ, values of leakage coefficient with a certain current in the armature. Show the influence of an increased pole arc. Give the results obtained by using the opposition method, with an ordinary voltmeter.

135. Distribution of Flux in an Air-Gap. — The actual distribution of flux in the air-gap of an electrical machine (Fig. 131) may be determined by inserting there a flat bismuth spiral (§ 165), or a flat coil

connected to a fluxmeter. These methods are more of an academical character, and are seldom used in practice.

The method actually used with direct-current machines involves the measurement of the e.m.f. induced in the armature coils when they pass through a certain point in the air-gap. Two small brushes are mounted on a temporary brush-holder, and the distance between them is adjusted to be equal to the distance between the centers of two adjacent commutator segments. The brushes are insulated from each other, and connected to a low-reading voltmeter. When the machine is revolving, these two "pilot" brushes measure in succession

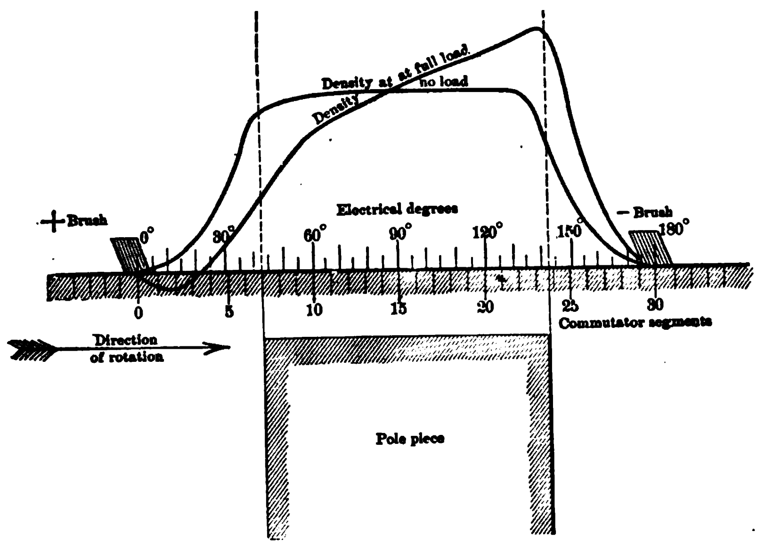

FIG. 131. Field distortion in a direct-current generator, due to the armature reaction.

the voltage at the terminals of all armature coils, when the same come into a certain position with respect to the field. In other words, they measure the voltage induced in a certain place of the field; this voltage is proportional to the flux density at the point under consideration.

By gradually moving the pilot brushes around the commutator, the distribution of the flux density may be measured from pole to pole; the results should be plotted as in Fig. 131. The same experiment, repeated with the armature loaded, gives a different distribution, because of the weakening and distorting action of the armature ampere-turns.

This method requires putting an extra brush-holder on the machine, and a divided sector for measuring angles. A simpler arrangement,

sufficiently accurate for practical purposes, was described in the *Electric Club Journal* 1904, p. 484. The device consists of a template made of cardboard, with holes for voltmeter points. The holes are spaced so as to correspond to a certain number of commutator bars. The template is laid around the commutator, as close as possible, but without touching it, and is securely fastened to the brush-holder. When the machine is revolving, voltmeter points are inserted in each two adjacent holes and the voltage measured. Ordinary metal points may scratch the commutator; it is better to use hard drawing pencils.

In alternators, the distribution of magnetic flux in the air-gap may be best determined by taking a curve of induced e.m.f. in an exploring coil placed on the armature. This can be done either by the point-to-point method (§ 647) or with an oscillograph (§ 650).

136. EXPERIMENT 6-G. — Determination of Magnetic Distribution in the Air-Gap of a D. C. Machine. — The purpose of the experiment is to obtain curves similar to those shown in Fig. 131; the method is described in the preceding article. Either two movable pilot brushes may be used, or a template and voltmeter points. (a) Bring the machine to full speed, run it light as a generator at normal voltage, with the regular brushes in the neutral line. Take the magnetic distribution curve, as shown in Fig. 131, by reading volts between consecutive commutator segments and angular positions of the contacts. (b) Take similar curves with the field, first highly saturated, and then with a very low saturation. (c) Load the machine on resistances and take similar curves; if possible again have the same three terminal voltages. The brushes should be set at the point of minimum sparking. (d) Run the machine as a motor, driving a generator; take the same three curves within as wide range of field currents as possible. (e) If a machine with compensating poles is available, take curves with and without the compensating winding; also, if possible, with the compensating winding connected in the wrong direction.

Report the results in the form of curves shown in Fig. 131; explain the observed differences in the distribution of the flux.

TESTS OF LIFTING AND TRACTIVE ELECTROMAGNETS.*

137. Electromagnets are used in practice for various duties, particularly for exerting mechanical pull, and for lifting weights. They are especially convenient for intermittent work, where a short stroke and quick action are required. They are used for releasing crane and

* Figs. 133 to 137 are taken by permission from Mr. C. R. Underhill's booklet, *Facts about Electromagnets.*

elevator brakes (Fig. 499), for operating switches and starters (Fig. 305), for supporting weights carried by a crane (Fig. 132). Electromagnets are also widely used as relays for closing all kinds of auxiliary or operating circuits (see Fig. 328).

Electromagnets used for heavy mechanical duty may be subdivided into two classes: lifting magnets and tractive magnets. The first (Fig. 132) are employed merely for supporting weights; the second (Figs. 133, 134, and 135) for performing certain work by the movement of a plunger. The characteristics of each class will be described separately.

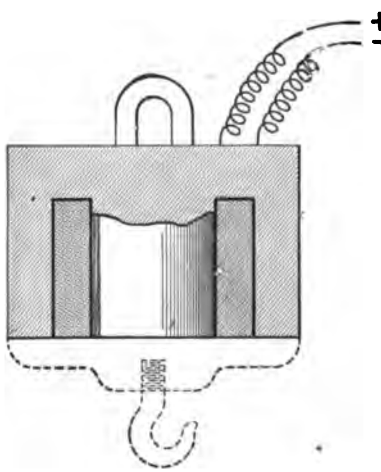

FIG. 132. A lifting electromagnet.

138. Lifting Electromagnets.—Electromagnets of this type, Fig. 132, are used in shops and in rolling mills where large pieces of iron are regularly carried by cranes. An electromagnet, suspended from a crane in place of the usual hook, is lowered to the piece of iron to be carried, and is energized. The piece is attached, and may be safely lifted by the crane. To release the piece, it is sufficient to open the exciting circuit of the electromagnet. The advantage of this method over the ordinary hook is that the work is performed more quickly, as no time is lost in fastening the hook, and in unhooking the piece at the end of the travel. The lifting electromagnet, shown in Fig. 132, consists of a steel casting with a circular hole in it for the exciting coil. Lines of force pass through the inside core, then through the object to be lifted, and the path is completed through the outside part of the electromagnet frame. The armature and the hook, shown in the sketch by dotted lines, are not used in regular operation; they are shown merely to indicate the way in which the electromagnet may be tested for tractive effort.

Lifting electromagnets are made of different shapes, according to the purpose for which they are intended to be used. Thus, in rolling mills, where large sheets are carried, lifting electromagnets are made with several short projecting poles, each provided with an exciting coil. This is done in order to support the sheet in several places simultaneously. For carrying pig-iron of irregular form, electromagnets are

provided with long, projecting poles, which may be sunk into a heap of pig-iron,—the pieces stick to the poles on all sides. To make the action still more effective, the poles, or fingers, may be made movable in the vertical direction, so that each pole is sure to come in contact with the heap.

The lifting power of an electromagnet depends not only on its construction and on the exciting current, but also on the form of the piece to be lifted, and on the quality of iron in it. This is because the magnetic flux is closed through the piece to be lifted; hence the reluctance of this piece determines the value of the flux. To make the conditions definite, when testing such an electromagnet, an armature should be used with the smallest possible reluctance; such an armature is shown by dotted lines in Fig. 132. Under such conditions the electromagnet develops the maximum possible lifting power. If, however, the electromagnet is intended for a definite service, for instance for lifting a certain kind of plates in a rolling mill, the test may be performed by using such plates, instead of an arbitrary armature.

139. EXPERIMENT 6-H. — Test of a Lifting Electromagnet. — Suspend the electromagnet (Fig. 132) from a secure place and provide an iron armature with a hook, as shown by dotted lines; weigh the armature before using it. Place the armature under the electromagnet, and gradually excite the coil until the armature is supported by the magnetic attraction. Note this critical value of the current. Place some weight on the hook, and increase the exciting current until it becomes again sufficient to support the armature. Proceed in this way until the saturation limit is reached, or until the limit of safe heating is reached. In performing this test, have under the armature a suitable support, preferably on springs, to limit the motion and to reduce the noise, when the armature is released and strikes the support. Perform the same test, varying different factors, *viz.:* (a) use a different armature; (b) interpose an air-gap, by placing a piece of paper, fiber, etc., between the magnet and the armature; (c) lift irregular objects. Before leaving the laboratory, measure the dimensions of the magnet and determine the number of turns in the exciting coil.

In the absence of a regular lifting magnet, the apparatus shown in Fig. 124 may be used for the experiment, and the influence of various factors investigated.

Report. Plot curves of pounds lifting power to amperes current as abscissæ. Figure out for a few points magnetic density B from the formula (3) in § 146. Show that this density checks within reasonable limits with that calculated from the number of exciting ampere-turns

and the dimensions of the magnet; use for comparison standard B-H curves given in various textbooks and pocketbooks. Discuss the influence of the various factors on lifting power.

140. Tractive Electromagnets. — Three common types of tractive electromagnets are shown in Figs. 133 to 135; the difference in their

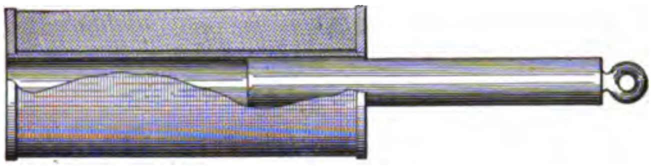

FIG. 133. A coil-and-plunger type tractive electromagnet.

characteristics may be judged from the curves of pull, in Fig. 136. The electromagnet, shown in Fig. 133, consists of a coil surrounding a plunger; the curve of pull shows that as the plunger is sucked into the coil the pull first increases and then again decreases. The addition of an iron frame on the outside (Fig. 134) increases the pull at the end of the stroke, as shown by the curve marked "Iron Clad." A further increase in pull is obtained by adding an inside core C (Fig. 135). The plunger is tapered and the core is countersunk, in order to increase the pull by reducing the reluctance of the air-gap; in many cases, however, flat-faced core and stop are sufficient. From the fact that an iron-clad

FIG. 134. An iron-clad tractive electromagnet.

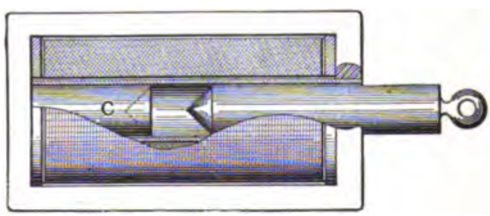

FIG. 135. An iron-clad tractive electromagnet, provided with a core C for increasing the pull at the end of the stroke.

electromagnet with a core gives the greatest pull it does not follow that this type should be used in all cases. The selection of one or another type depends upon the character of the work for which the magnet is intended. Knowing the requirements of a particular case, the best type may be selected with reference to the curves of pull.

A convenient apparatus for testing tractive electromagnets is shown in Fig. 137. The coil *C* of the electromagnet under test is connected to a D. C. supply, through the switch *S*, regulating rheostat *R*, and the ammeter *A*. The plunger *P* is suspended from the beam of a balance

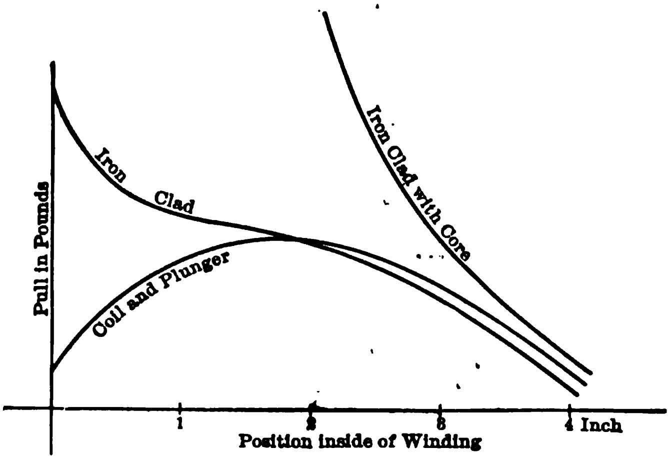

Fig. 136. Curves of comparative pull of the electromagnets shown in Figs. 156 to 158.

The balance has fulcrums at F_1 and F_2, and two sliding weights w_1 and w_2. With this construction of the balance large pull is counter-

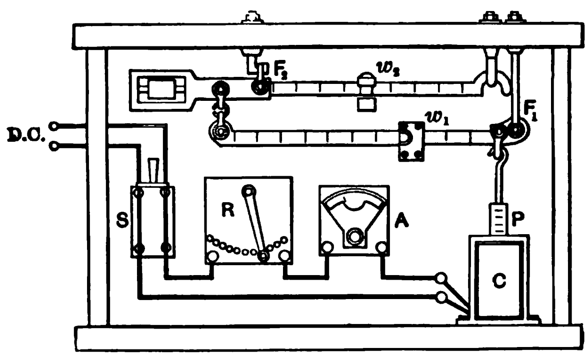

Fig. 137. An apparatus for testing tractive effort of electromagnets.

balanced with small weights; the apparatus is thereby made sensitive and convenient to handle. The curves shown in Fig. 136 were taken by means of this device.

141. EXPERIMENT 6-1. — Test of a Tractive Electromagnet. — The purpose of the experiment is to determine curves of pull (Fig. 136)

of different forms of tractive electromagnets. An apparatus, similar to that in Fig. 137, is convenient for the purpose. (a) First test an electromagnet of the type shown in Fig. 133; take curves of pull with a certain position of the plunger, through a wide range of exciting currents. (b) Repeat the same test with different positions of the plunger. (c) Then take the same coil and provide it with an iron core, as in Fig. 134. Perform a similar test throughout the same range of currents and with the same positions of the plunger. (d) Finally put an inside stop C (Fig. 135) into the coil and test the magnet again for pull.

Report. Plot curves showing variations of the pull with the position of the plunger; also curves showing variations in pull with the exciting current. Give a theoretical justification for the general form of the curves.

CHAPTER VII.

PERMEABILITY TESTS.

142. STEEL and iron used in the construction of electrical machinery must possess a high *permeability*, or high magnetic conductivity. This means that a required magnetic flux should be produced with the smallest possible number of exciting ampere-turns. Many devices have been elaborated for testing permeability of steel and iron, so that it becomes a rather difficult task to give a classification of the pieces of apparatus used. The principal distinction between types seems to be in the method used for measuring magnetic flux. From this point of view, the devices described below may be subdivided into those in which the flux is measured:

(1) By tractive effort;
(2) By inductive discharge through a ballistic galvanometer;
(3) By a steady magnetic or electric action;
(4) By an increase in the electrical resistance of bismuth.

Before describing the testing devices proper, it is necessary to review some points of general theory, and to indicate the manner in which results of permeability tests should be grouped for purposes of practical comparison.

143. Magnetization or B-H Curves. — The most convenient way to represent results of a permeability test on a sample of steel or iron is to plot the results in the form of a curve (Fig. 128) which gives the number of ampere-turns per unit length of the sample, necessary to produce in it a certain flux density B. The designer is immediately enabled to compute the number of ampere-turns required for the excitation of a frame of given dimensions in order to obtain a desired magnetic flux.

The older way was to plot flux densities B in iron to flux densities H which would take place if iron were removed and substituted by air. A curve of this kind shows how many times the flux has increased because of the presence of iron; in other words, it shows how many times the permeability of iron is greater than that of air. The permeability of air is arbitrarily fixed as of unity value so that the ratio $B \div H$ gives directly the permeability of iron. But the numerical value or permeability is of slight importance in practical work; what is needed is

the number of ampere-turns for producing a required flux density in iron. This number must not be above a certain limit, otherwise the steel is rejected as being of an inferior magnetic quality.

The name *B-H* curves is, however, retained for curves plotted to ampere-turns as abscissæ; it simply means, that the curve shows a relation between a flux and the exciting ampere-turns which produce it. Another common name for *B-H* curves is *magnetization* curves. Both names are used below indiscriminately.

144. Hysteresis Loop. — Magnetization, or *B-H* curves (Fig. 138) should be taken with the exciting current both increasing and decreasing;

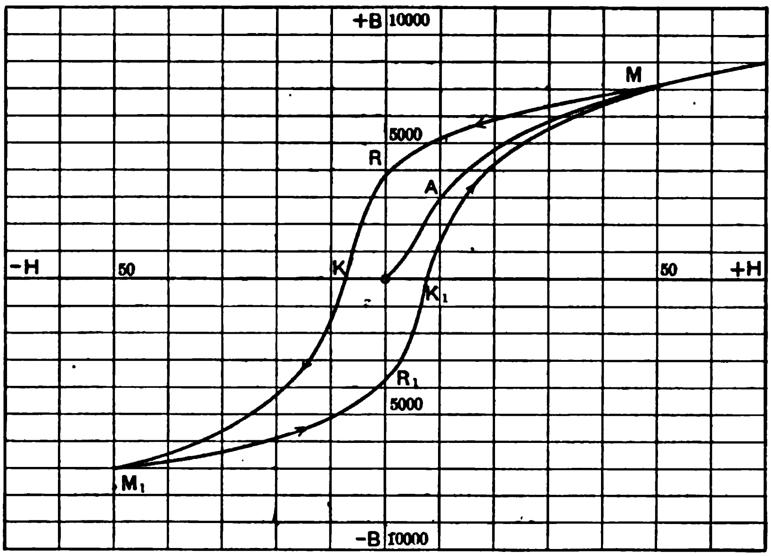

FIG. 138. Magnetization curve and hysteresis loop of a sample of iron.

also with the current reversed, for the reason that the flux density at a given excitation depends somewhat upon the previous state of magnetization in the sample. Assume first, that the sample is altogether free from magnetism, Gradually increasing the excitation gives the curve *OAM*; this is called the virgin curve (Jungfrauliche Kurve). When now the excitation is reduced again, the flux density does not decrease as rapidly as it increased, but varies according to the curve *MR*. When the exciting circuit is opened, the iron still possesses a *residual* magnetic density *OR*. Reversing the exciting current, this density is gradually decreased; the iron being deprived of its residual magnetism, when the exciting ampere-turns = *OK*. When the exciting current is further

increased (in this reverse direction), the magnetization in the iron is reversed, and varies according to the part KM_1 of the curve. Decreasing the current again, and reversing it makes the densities vary according to the branch $M_1 K_1 M$ of the curve.

This peculiar phenomenon, — that two different densities are possible with the same value of exciting current, — is called *hysteresis*. It is attributed to some kind of molecular friction in iron; the root of the word signifies "to lag behind." The curve $M K M_1 K_1$ is called the hysteresis loop. In accurate permeability tests, it is advisable to take both the virgin curve and the hysteresis loop.

A large value of residual magnetism OR is objectionable in cases where the flux is supposed to follow closely any variations of the exciting current, as — for instance — in fields of generators and motors. On the other hand, large residual magnetism is desirable in steel intended for permanent magnets, such as are used in measuring instruments, and in telephone instruments.

145. Magnetic Flux in Air. — In some of the tests, described below, it is required to figure out ampere-turns necessary for producing a certain flux density in air, instead of iron. This can be done with sufficient accuracy, only when the lines of force are parallel to each other, as for instance in a small air-gap between two large pieces of iron, or within a long solenoid. Theory and experience show, that under these conditions one *ampere-turn per* 1 *cm. length of path in air produces a flux density* $H = 1\frac{1}{4}$ *lines of force* (maxwells) *per sq. cm.* (more accurately $\frac{4\pi}{10} = 1.257$). Magnetic densities in air are usually denoted by H to distinguish them from those in iron, which are designated by B. Thus to produce a density H in an air-gap l cm. long (in the direction of lines of force)

$$ni = 0.8\,Hl \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

ampere-turns are required. If l is in inches, and H in lines per 1 sq. inch, the formula becomes

$$ni = 0.796\,\frac{H}{(2.54)^2} \times (2.54\,l) = 0.313\,Hl \quad . \quad . \quad . \quad . \quad (1a)$$

Let it be necessary, for instance, to produce a flux of 300,000 lines in an air-gap 0.3 cm. long, and of a cross-section of 50 sq. cm. The flux density $H = 300{,}000/50 = 6000$ maxwells per sq. cm. If the air-gap were 1 cm. long, the necessary number of ampere-turns would be $0.8 \times 6000 = 4800$. As the air-gap is only 0.3 cm. long, the actual number is $0.3 \times 4800 = 1440$ ampere-turns.

A theoretical proof of the expression (1) may be found in any standard textbook on electricity and magnetism. For practical purposes it is sufficient to accept this expression as an experimental fact, which has been verified a great many times in actual practice.

TRACTIONAL METHOD.

146. Thompson Permeameter. — One of the simplest pieces of apparatus for testing iron and steel, the so-called *Thompson permeameter*, is shown in Fig. 139. It is based on the measurement of the mechanical force necessary for separating two parts of a magnetic circuit. The sample T to be tested is made in the form of a rod; it is placed within an iron yoke y, of a negligible magnetic resistance (reluctance). The closed iron circuit thus formed is magnetized by the coil C. Then the sample T is pulled out of the yoke by turning the handwheel H; the pull is read on the spring balance B.

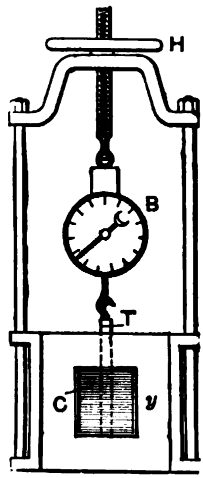

FIG. 139. Thompson permeameter.

The apparatus is intended primarily for approximate relative measurements; the better the sample (the higher its permeability) the more force is required to pull it out of the yoke, with the same magnetizing current. The device is used for such approximate tests by some electric manufacturing companies. Whenever a new lot of the material is received, samples of it are tested in the permeameter; the force necessary to pull the specimens out of the yoke must be at least equal to that previously found for the lowest acceptable grade of material, otherwise the entire consignment is rejected. A knowledge of the *absolute* value of permeability is not necessary in this case. The number of turns on the field windings of machines cannot be changed to suit the permeability of each lot, but is designed for a certain average grade of iron. The right number of ampere-turns in each individual machine is obtained by regulating its field rheostat, so as to get the desired voltage.

The permeameter may also be used for determining actual magnetization curves (Fig. 138) of samples; this is done by comparing the force necessary for pulling out the sample under test, to that required with a standard sample whose magnetization curve has been previously determined by some other method. The comparison is made on the basis of the fact, that the mechanical force of attraction between two

parts of a magnetic circuit is proportional to the square of the magnetic density at the separating surface (Maxwell's law). This law may be deduced as follows: The attraction at the separating surface may be imagined as due to two equal and opposite magnetic masses. When the magnetic density increases n times, each mass increases n times. The force of attraction is proportional to the product of the masses; therefore it increases n^2 times.

Thus with the same magnetizing current, if F_1 is the spring balance reading with the sample under test, and F_2 that with the standard sample, we have

$$\left(\frac{B_1}{B_2}\right)^2 = \frac{F_1}{F_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If magnetic density B_2 is known from the magnetization curve of the standard sample, B_1 may be calculated, and the magnetization curve for the sample under test plotted.

The magnetization curve of a sample can be obtained with the Thompson permeameter even without having a standard sample: Let B be the magnetic density in the sample (number of lines of force per sq. cm.); S the cross-section of the rod, and F the pull (in dynes). The force of attraction is proportional to the square of density and to the surface S of contact between the sample and the yoke. From theoretical considerations, if F is in dynes, the coefficient of proportionality is $1/8\pi$. Thus we have:

$$F = \frac{1}{8\pi} . \ S \ (B - H)^2,$$

where H is the number of lines of force per sq. cm. left in the air after the sample has been pulled out. $(B - H)$ is introduced into the formula instead of B, because only $(B - H)$ lines fo force are "broken" when the sample is removed. From the above formula, substituting practical units, we get

$$B = 1317 \sqrt{\frac{F}{S}} + H \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

where B and H are as before magnetic densities per sq. cm., S is the cross-section of the sample in sq. inches, and F is the pull in lbs. H is calculated from the formula (1) given in § 145:

$$H = \frac{4\,\pi}{10} \cdot \frac{ni}{l} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where ni is the number of ampere-turns of the magnetizing coil, and l is its length in cm. If l is expressed in inches the formula becomes

$$H = 0.495 \cdot \frac{ni}{l}.$$

The values of B and H per square inch are 6.45 times higher than those expressed per sq. centimeter.

The Thompson permeameter is adapted for quick comparative tests rather than for taking exact magnetization curves. A spring balance is not reliable enough to allow of accurate measurements, and moreover the results are vitiated by two air-gaps between the yoke and the sample. To reduce the error due to this cause the sample must fit nicely into the hole in the upper part of the yoke, and the two surfaces to be pulled apart must be well planed.

Another device based on the same principle is the Ewing magnetic balance. It has a beam with a sliding weight instead of a spring balance; the specimen rests on the yoke with its cylindrical surface, instead of touching the yoke with an end, as in the Thompson permeameter. This feature does away with the planing of one end of the sample, and makes it unnecessary to have a hook on the other end; besides this, a more uniform contact is obtained. The scale is calibrated directly in flux densities by means of a standard sample, previously tested by some other method.

147. EXPERIMENT 7-A. — Magnetization Curves of Iron with Thompson Permeameter. — The purpose of the experiment is to obtain for given samples B-H curves as shown in Fig. 138, or in Fig. 128. It is desired that the student test samples of cast steel, wrought iron, and cast iron, to see the difference in the magnetic properties of these materials. (a) A sample must be demagnetized before beginning the experiment. For this purpose it is put in the apparatus, and magnetized as highly as possible; then the exciting current is gradually reduced to zero, meantime being constantly reversed. Or else the sample may be magnetized with an alternating current, and gradually withdrawn from the coil. (b) First take a virgin curve OAM; read amperes excitation and lbs. tension necessary to tear the sample from the yoke. Carry the magnetizing current as high as the coil will permit. Then take a complete hysteresis loop. (c) Repeat the same test with other samples. Before leaving the laboratory, measure the cross-section of the samples tested, and the axial length of the coil; also ascertain the number of turns in the coil.

The permeameter is not a very accurate instrument, and each point

should be obtained as an average of several readings. See that the sample and the yoke are nicely surfaced and that the spring balance exerts an axial pull. Another precaution, important in all permeability tests, is that once the current is raised to a certain value, it should not be reduced again, until a branch of the magnetization curve is completed. Otherwise indefinite hysteresis effects are introduced.

Report. Plot lbs. pull to exciting amperes as abscissæ, for all the samples tested. Do this before making any calculations, in order to obtain smooth curves and to eliminate possible errors of observation. Change the curve for one of the samples into a magnetization curve, shown in Fig. 128, by using formula (3). Use ampere-turns per inch as abscissæ, maxwells per square inch as ordinates. If the sample was previously tested by another method, check the results. With this

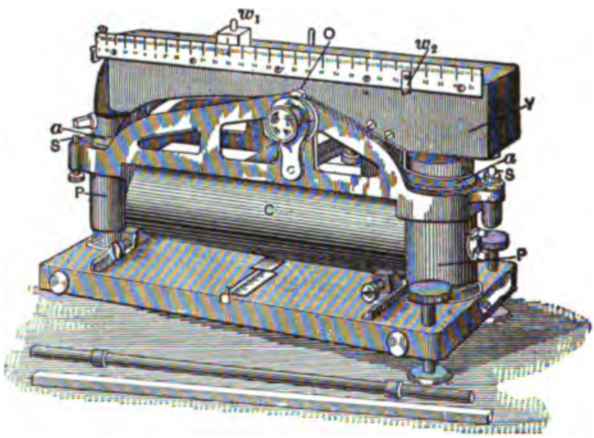

FIG. 140. Du Bois magnetic balance.

curve as a standard, plot a similar curve for another sample, using formula (2).

148. Du Bois Magnetic Balance. — This also is a tractional device (Figs. 140 and 141), more sensitive and accurate than the two devices described in § 146. The sample under test, T, is clamped between two heavy pole-pieces PP and magnetized by the coil C. Clamps are provided for accommodating either a round or a square sample; also a bundle of laminations. Two specimens are shown lying on the table in Fig. 140. The magnetic circuit is closed through the iron yoke YY; the yoke is supported by knife-edges at O, like the beam of a balance. The shorter arm of the yoke is made of the same weight as the longer one, by weighting it with lead; the yoke is in balance when the coil C is not energized and the weights W_1 and W_2 are on zero.

When the sample is magnetized, the yoke tips over to the left, because the attraction in the left-hand air-gap acts on a longer lever. To bring the yoke in balance the weights are moved to the right. When the balance is obtained, the flux density in the sample is read directly on the scale, in maxwells per sq. cm. The movement of the yoke is limited by adjustable stops, *SS* (Fig. 140). To simplify the balancing, the stops on one side may be provided with platinum tips, and connected to a local circuit consisting of a dry cell and a bell or a galvanometer; a signal is given when the yoke touches one of the stops.

A certain flux in the sample and in the pole-pieces gives a definite force of attraction at the air-gaps *aa*. Therefore the scale of the instrument could be calibrated directly in fluxes. But as all samples are of the

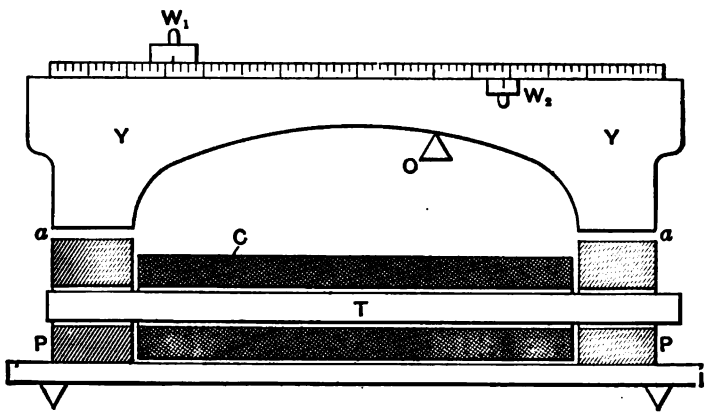

FIG. 141. Schematic representation of the Du Bois magnetic balance.

same cross-section, to each flux corresponds a definite density. Therefore the scale is calibrated directly in magnetic densities. The calibration is done by means of a specimen whose magnetization curve has been determined by some other method. A good feature of the instrument is that the reluctance of the air-gaps is large as compared to that of the sample; in this way small inaccuracies in the contacts between the sample and the pole-pieces are of no consequence.

149. EXPERIMENT 7-B. — Magnetization Curves of Iron with Du Bois Balance. — The experiment is performed in the same order as the experiment 7-A (§ 147). Before leaving the laboratory weigh the sliders, measure the length and the cross-section of the air-gaps and their horizontal distance from the knife-edge supports. Make a copy of the scale; measure the cross-section of the samples; note the number of turns in the magnetizing coil.

Report. (1) Plot of curves of flux density to ampere-turns per cm. (or inch) as abscissæ (Figs. 128 and 138). If possible, use the same sheet of cross-section paper for all the samples, so as to have a direct comparison for the quality of the materials. (2) Show in a numerical example how to use these curves for determining the number of ampere-turns required to produce a given flux in a magnetic circuit. Take, for example, a circuit like the one shown in Fig. 124. The dimensions of the cores and the length of the air-gap are supposed to be given. (3) Figure out the actual pull on the yoke of the balance with a given flux (§146); see how closely the calculated magnetic torque checks with that of the weights.

BALLISTIC METHOD.

150. In taking magnetization curves two quantities are to be measured, — exciting ampere-turns and the flux produced by them. The chief difficulty lies in measuring the flux. It can be measured much more accurately by a discharge through a ballistic galvanometer than by tractive methods described in §§ 146 and 148. The use of the ballistic galvanometer for measuring fluxes is described in §§ 119 and 122. While this is the most accurate method for measuring fluxes, it was not until recently that devices have been perfected such as make the method convenient for technical purposes. It may not be amiss to give here a brief history of the development of this method.

151. The Development of the Ballistic Method. — The original arrangement (Fig. 142) required samples to be made in ring form, each wound separately with exciting and secondary coils. This, of course, was a serious objection from a practical point of view. Hopkinson introduced the "divided-bar" apparatus (Fig. 143) in which the samples *TT* are made in the form of rods; these are much easier to prepare than rings. Permanent coils are used; the magnetic circuit is closed through a heavy yoke *YY*. An objection to this method is that — due to the necessarily imperfect contacts between the yoke and the samples, — the quality of iron appears worse than it is in reality (see Fig. 128).

Ewing remedied this by testing samples with two different lengths of the magnetic circuit (Fig. 144); the resistance of the contacts is eliminated from two measurements. His method is objectionable, because it requires two identical samples, which sometimes are difficult to get. Picou, on the other hand, eliminated the influence of contacts (Fig. 146) by additional windings which compensate for the reluctance of the air-gaps. With all these improvements there still was a need for an apparatus for measurement of permeability of large castings as a whole,

without preparing special samples. Dr. Drysdale's permeameter (Fig. 147) fills this demand.

Another objection to the ballistic method has been found in the ballistic galvanometer itself; in its original form, with a telescope and with undamped swings, it was not a convenient device for practical work. Here also considerable progress has been made of late. Ballistic galvanometers of sufficient sensitiveness are now to be had, that are provided with a pointer and a scale, like ordinary voltmeters and ammeters; moreover, they are made perfectly damped electromagnetically, so that readings may be taken in quick succession. Finally the advent of the fluxmeter (§ 120) makes it possible to obtain continuous indications of fluxes instead of instantaneous deflections of a ballistic galvanometer.

The above-mentioned devices, based on the ballistic method, will now be described more in detail.

152. Ring Method. — The sample of iron or steel to be tested is turned in the form of a ring *I* (Fig. 142) of a comparatively small radial

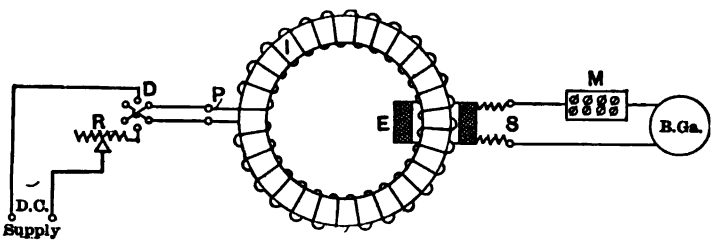

FIG. 142. Testing permeability of a sample in ring form.

breadth. If sheet steel is to be tested, separate rings are punched, assembled together, and turned down on the sides. The ring is uniformly wound with a known number of turns of wire, connected to the terminals *P* (primary). A secondary or exploring coil *E* is wound on the first coil and connected to a ballistic galvanometer. The core is excited from a source of D. C. supply, through a regulating rheostat *R* and a double-throw switch *D*. An ammeter, not shown in the figure, is connected into the primary circuit. It is thus the same arrangement as is shown in Fig. 124 and described in §§ 117 and 118, except that the magnetic circuit is perfectly closed, and no inaccuracy is produced by an air-gap.

The sample is thoroughly demagnetized by exciting it to as high saturation as possible, and then gradually reducing the excitation to zero, at the same time continually reversing the current. After this, the

sample is magnetized again in steps, and the corresponding deflections of the galvanometer are noted. This gives the virgin curve (Fig. 138); a complete hysteresis loop may also be taken in a similar way, if desired. The curves shown in Figs. 128 or 138 may be plotted by knowing the dimensions of the core, the number of turns on both windings, and the constant of the ballistic galvanometer.

In some cases it is possible to have specimens in the form of very long rods. Experience shows that a rod whose length is at least 500 times its diameter may be considered magnetically as infinitely long. This means that the same number of ampere-turns *per inch* are required in order to produce a certain flux, whether the rod is straight or made into a closed ring, without air-gap. This is not true for shorter rods on account of demagnetizing action of the ends; again, with a very long rod

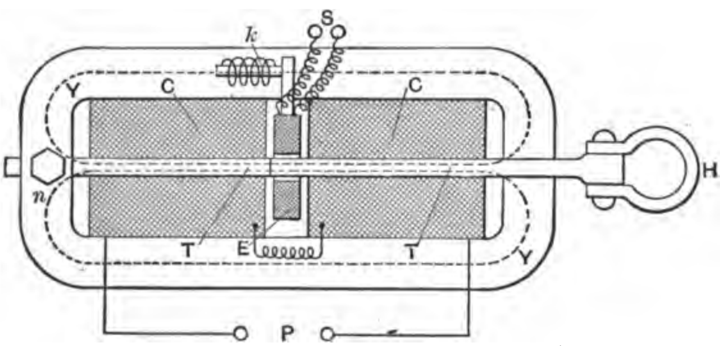

Fig. 143. Hopkinson divided-bar method for testing iron.

the reluctance of the path of lines of force back through the air is practically zero, on account of a very large cross-section of this path. For this reason the required number of ampere-turns is the same as if the rod was bent into a ring.

When such a rod is available for test, it is inserted in a straight coil which is slightly longer than the sample, and is tested as in Fig. 142.

153. Divided-Bar Method. — An objection to the practical use of the ring method is that the preparation of samples is rather complicated. Hopkinson found a way out of this difficulty by making samples in the form of two straight bars, *TT* (Fig. 143). The magnetic circuit is closed through a heavy iron yoke *YY* of negligible reluctance; so that the reluctance of the circuit is practically caused by the samples alone. The left-hand bar is securely clamped to the yoke by the screw *n*. The right-hand bar is provided with a handle *H*, by means of which it may be pulled out of the yoke. The exciting or primary coil *C* is wound in two sections; it is connected to the terminals *P*.

The exploring coil E is inserted between the two sections and is connected to the terminals S. The electrical connections are the same as in Fig. 142.

To measure the flux produced in the samples by the coils CC, the right-hand sample is suddenly withdrawn from the yoke. This releases the coil E, and the spring k instantly snaps it out of the magnetic circuit. The change in flux embraced by this coil produces a discharge in the ballistic galvanometer, as in the ring method.

Instead of using two samples and pulling out one of them, one long sample may be used, and the ballistic discharge obtained by changing or reversing the current in CC, as in the ring method. The apparatus is fairly accurate for practical purposes, but great care must be exercised to have good magnetic contacts between the yoke and the sample.

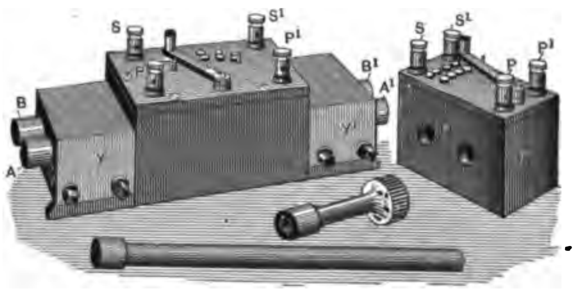

FIG. 144. Ewing double-bar method for testing iron.

154. Ewing Double-Bar Method. — To eliminate the influence of contacts and the reluctance of the yoke, Ewing suggested the apparatus shown in Fig. 144.* The magnetic circuit is formed by two test bars AA', BB', and two heavy yokes YY' made of wrought iron. Each bar is surrounded by a magnetizing coil, as in Fig. 154. A secondary coil, connected to a ballistic galvanometer, is wound on one of the exciting coils. The coils are mounted in the wooden case C; the terminals PP' are connected to a source of D. C. supply, the terminals SS' to a ballistic galvanometer. The number of turns in the secondary coil may be varied at will by the switch shown on top of the box. At the same time some resistance is automatically inserted into the galvanometer circuit, as the sections of the coil are cut out. In this way the resistance of the galvanometer circuit is kept constant, and its deflections made proportional to the number of secondary turns. The reason for varying the number of turns is to have galvanometer deflections within its best range with widely different values of the flux.

* Fig. 144 is taken, by permission, from Prof. E. S. Ferry's *Practical Physics*, Vol. III.

The test is performed exactly as with the ring method. After a magnetization curve has been obtained, one of the yokes and the box *C* are removed by loosening the screws. A shorter box *D* is slipped in place, and the magnetic circuit completed again, the yokes being brought closer together. A magnetization curve is taken as before. It differs from that previously obtained because of a shorter length of the circuit and a smaller number of magnetizing turns in the box *D*. The magnetic resistance of the yokes and of the contacts is the same in both cases, and may be eliminated by comparing the two curves. Let, for instance, 850 ampere-turns be necessary in order to produce a certain flux with the box *C*, 10 inches long; let 450 ampere-turns give the same flux with the box *D*, 5 inches long. This shows that 400 ampere-turns were used in the first case for $5 \times 2 = 10$ inches of the length of the

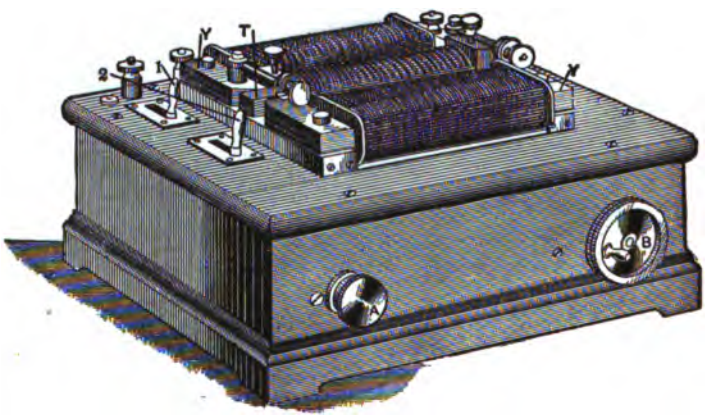

FIG. 145. The Picou permeameter.

samples, so that the true ampere-turns per inch of the sample are: $400/10 = 40$. If the shorter box were not used, the reluctance of the contacts and the yokes would have to be neglected; the number of ampere-turns per inch of the sample would have to be taken as $850/20 = 42.5$, which is about 6 per cent too high. The experiment with the shorter box enables one to separate the 50 ampere-turns lost in overcoming the reluctance of the contacts and the yokes.

The details of the apparatus shown in Fig. 144 are due to Prof. J. W. Esterline; in particular he deserves credit for the boxes, the method of clamping, and for the scheme of using variable secondary turns with constant resistance.

155. Picou Permeameter.—In this apparatus (Fig. 145) the disturbing influence of the contacts is compensated by additional magnet-

izing windings. The principle of compensation is shown in Fig. 146. The sample T under test is made rectangular, or consists of a bunch of steel laminations. It is clamped within the magnetizing coil C_3 between two U-shaped yokes YY, provided with compensating windings C_1, C_2. The winding C_3 supplies just enough ampere-turns to carry the flux through the test sample alone; the coils C_1 and C_2 provide the magnetomotive force necessary for overcoming the reluctance of the yokes and the air-gaps. A secondary coil is wound on each of the three magnetizing coils, and may be connected at will to a ballistic galvanometer.

The first step in testing a sample is to compensate for the reluctance of the yokes and the air-gaps. For this purpose the circuit of the main coil C_3 is left open; the coils C_1 and C_2 are energized so as to produce

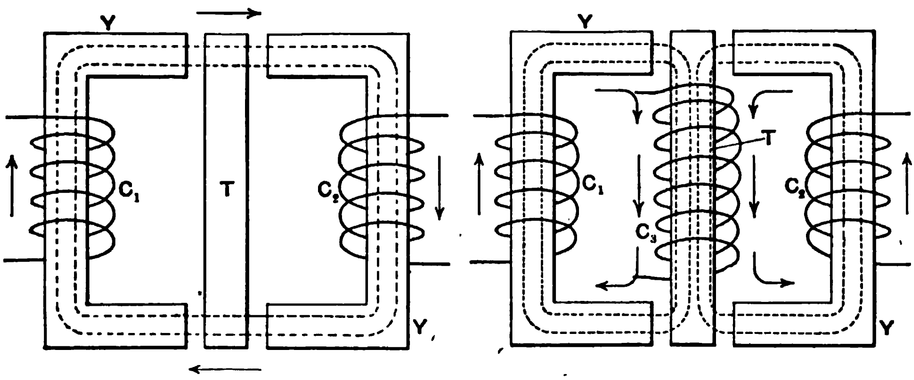

FIG. 146. Principle of compensation for the reluctance of air gaps, in the Picou permeameter.

a flux through the yokes only, as shown by dotted lines in the sketch to the left. Each coil supplies the ampere-turns necessary for overcoming the reluctance of one yoke and two air-gaps. The desired value of the flux is established by trial discharges through the ballistic galvanometer. Now the current in one of the coils is reversed, so that the flux is deflected into the sample under test, as shown by dotted lines in the sketch to the right. Each of the coils, C_1 and C_2, has now to overcome the reluctance of its yoke, of two air-gaps, and in addition the reluctance of one longitudinal half of the sample under test. The flux is naturally reduced; to bring it to its former value, the middle coil C_3 is excited so as to assist the two other coils.

When the former value of the flux is established in the yokes (as recognized by ballistic deflections), it is evident that the two outside coils again supply the ampere-turns necessary for the yokes and the gaps, while the middle coil carries the flux through the sample under

test. Knowing the number of ampere-turns per inch in the coil C_3 and taking a ballistic discharge through the secondary coil which surrounds it, a set of data is obtained for the magnetization curve. The same test is repeated with other values of flux.

All the necessary adjustments and changes of connections are conveniently performed by means of the levers 1 and 2 and handles *A* and *B* (Fig. 145).

156. Drysdale Permeameter. — This instrument, shown in Figs. 147 to 149, is used for testing frame castings of electric generators

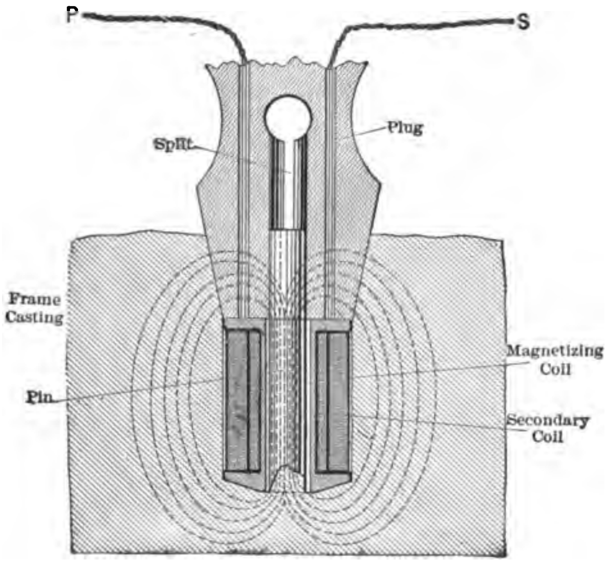

FIG. 147. Cross-section of the Drysdale permeameter, showing the plug in the casting under test.

and motors, without preparing special samples. The magnetizing and the exploring coils (Fig. 147) are wound on a plug (Fig. 148); the

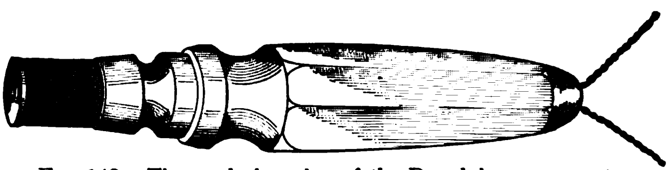

FIG. 148. The exploring plug of the Drysdale permeameter.

plug is inserted into a hole drilled at any desired place of the casting to be tested. The magnetic circuit is excited as shown by dotted lines, and a discharge taken through a ballistic galvanometer, or a fluxmeter.

The hole in the casting has the form shown in Fig. 149. The pin left in the center constitutes the sample under test. A special hollow drill (Fig. 149) is used for making these holes, so that they will exactly fit the testing plug. It is well to test a casting in several places, in order

FIG. 149. The drill and the sample prepared by it, for use with the Drysdale permeameter.

to get its average permeability. The instrument is calibrated empirically by a sample of known magnetic properties.

157. Theory of the Ballistic Galvanometer. — The methods described in §§ 152 to 156 require the use of a ballistic galvanometer. The general features of the instrument are described in § 119; a proof will now be given that its deflections are proportional to variations in the flux through the secondary coil. It will be proved (a) that electrical discharges through the galvanometer are proportional to variations in flux, and (b) that galvanometer deflections are proportional to electrical discharges. From these two facts will follow immediately that deflections are proportional to variation in flux.

(a) *Electrical discharges through a ballistic galvanometer are proportional to changes in flux.* Let N be an instantaneous value of a variable magnetic flux; the instantaneous e.m.f. e induced by a variation of this flux in an exploring coil that surrounds it is, according to § 118,

$$e = s \cdot \frac{dN}{dt} \cdot 10^{-8},$$

where s is the number of turns in the coil. Let r be the total resistance of the galvanometer circuit, L its inductance; according to the equation (6), in § 103, the instantaneous current i in the galvanometer is determined by the relation

$$e = ir + L\frac{di}{dt} \cdot$$

Substituting e from the above gives

$$s \cdot \frac{dN}{dt} \cdot 10^{-8} = ir + L\frac{di}{dt},$$

or

$$s \cdot dN \cdot 10^{-8} = ir \cdot dt + L \cdot di.$$

Let N_1 and N_2 be the initial and the final values of the flux during the short period t of the change. Integrating the preceding equation over the period t we obtain

$$s\,(N_1 - N_2)\,10^{-8} = r\int_0^t i dt + L\,(i)_0^t.$$

The integral on the right side represents the total quantity of electricity in coulombs or ampere-seconds which are discharged through the galvanometer; let this discharge be denoted by Q. The second term to the right $= 0$, because the current is zero at the beginning and at the end of the discharge period. Thus we have

$$s\,(N_1 - N_2)\,10^{-8} = rQ \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

This proves the above statement that an electrical discharge through the galvanometer is proportional to the variation in the flux.

(b) *Deflections of ballistic galvanometer are proportional to brief discharges through it.* After an electric discharge has passed through the moving coil of a galvanometer, the coil begins to move against the following forces:

(1) Torsion of the suspension wire, or the springs.
(2) Currents induced in the coil and in its aluminum frame.
(3) Air resistance.

Let the final deflection be α_1 degrees with a given discharge of Q coulombs. The force of torsion is proportional to the angle of torsion; thus the total resisting impulse of the suspension wire is proportional to

$$\int_0^{\alpha_1} \alpha \; dt.$$

The currents induced during the movement of the coil are proportional to instantaneous angular velocities $d\alpha/dt$; their impulse is proportional to

$$\int_0^{\alpha_1} \left(\frac{d\alpha}{dt}\right) dt = \alpha_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

Now suppose a different discharge Q_2 to be sent through the galvanometer, such that the new angle of deflection $\alpha_2 = 2\,\alpha_1$. The time of one swing of the galvanometer is practically independent of the angle of deflection (as in the pendulum); therefore all intermediate angles α and angular velocities must be doubled. Thus the impulse of the suspension wire is doubled, and that of the induced currents. Therefore Q_2 must be $= 2\,Q_1$ in order to give a double moving impulse. This proves that electrical impulses, or discharges, and galvanometer deflections are proportional. The air resistance is not exactly proportional to angular

velocity, and therefore somewhat vitiates the result; but its influence is usually negligible.

The same theory applies to the fluxmeter (§ 120), only the time of the discharge does not influence the results. This is because the instrument possesses no resisting torsion, and all of the electric impulse is absorbed by induced currents, according to expression (5).

(c) *Final formulæ.* Denoting the galvanometer constant by b, we have

$$Q = b\alpha \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

where α is the scale deflection. Consequently

$$s(N_1 - N_2)10^{-8} = br\alpha \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Let, for instance, the constant of the galvanometer be $b = 15 \times 10^{-6}$ coulombs (ampere-seconds) per 1 cm. of scale deflection; let the resistance of the galvanometer circuit, r, equal 2000 ohms, the number of turns in the exploring coil $s = 100$. A certain flux was established through the coil, and then the exciting circuit suddenly opened, causing a galvanometer deflection $\alpha = 30$ cm. The final flux $N_2 = 0$, and we have

$$N_1 = \frac{10^8}{100} \times 15 \times 10^{-6} \times 2000 \times 30 = 900{,}000 \text{ maxwells.}$$

158. Calibration of a Ballistic Galvanometer. — Ballistic galvanometers are usually calibrated with a standard condenser or with a standard inductance coil.

(a) Let a condenser of a known capacity of C microfarads be charged at a certain voltage e, and then discharged through the ballistic galvanometer; let the deflection be α. According to the definition of capacity (§ 426, Vol. II), the charge $Q = Ce \,.\, 10^{-6}$ coulombs, so that, with reference to equation (6), we have $Ce \,.\, 10^{-6} = b\alpha$. All quantities in this equation are known, except b, which can be determined. See also the note at the foot of page 188.

(b) A standard coil is a long solenoid without iron, with an exploring coil placed about its central part. According to the equation (1) in § 145, the flux density in the middle part of the coil

$$H = \frac{4\pi}{10} \cdot \frac{ni}{l}.$$

If the cross-section of the coil is A sq. cm. the total flux $= AH$. The coil is excited with a known current i, and the circuit opened, producing a discharge in the ballistic galvanometer. According to the equation (7) we have

$$sAH \,.\, 10^{-8} = br\alpha,$$

from which b may be calculated.

159. EXPERIMENT 7-C. — Magnetization Curves of Iron by the Ballistic Method. — The experiment comprises the use of any of the instruments described in §§ 152 to 156. The sample is thoroughly demagnetized, and a virgin curve *OAM* (Fig. 138) taken. After this one or more hysteresis loops may be taken. The test should be performed on samples of steel, soft wrought iron, and cast iron. If the constant of the ballistic galvanometer is not known, the instrument must be calibrated as explained in the preceding article. Aside from learning the method itself, and the operation of a permeameter, it is expected that the student will make clear to himself: (a) The details of its construction, (b) the sources of error, (c) the limits of accuracy.

Report. (1) Plot the magnetization curve of one sample, using ampere-turns per inch as abscissæ and B per square inch as ordinates; for another sample use densities H in air as abscissæ and B per sq. cm. as ordinates; a third curve should give values of permeability $B \div H$ to densities B as abscissæ. In this way the student will learn the various methods of plotting magnetization curves.

(2) Illustrate by a numerical example the use of these curves for determining the number of ampere-turns in a given case, — for instance, to produce a given flux in a magnetic circuit like the one shown in Fig. 124. The dimensions of the cores and the length of the air-gap are supposed to be given.

(3) Figure out hysteresis loss by integrating one of the curves, as explained in § 183.

(4) Discuss the advantages and disadvantages of the apparatus used, sources of error, limits of accuracy, etc.

STEADY DEFLECTION METHODS.

160. Koepsel Permeameter. — In its principle the device is a milli-voltmeter (Figs. 150 and 151), in which the permanent magnet is replaced by an electromagnet; the sample under test is a part of this electromagnet. The instrument consists of two heavy pole-pieces J, J (Fig. 150) in which is fastened the rod P to be tested; S is the magnetizing coil. The flux produced in the sample and in the pole-pieces is measured by means of a moving coil s, similar to those used in direct-current ammeters and voltmeters (Fig. 34). The coil is supplied with

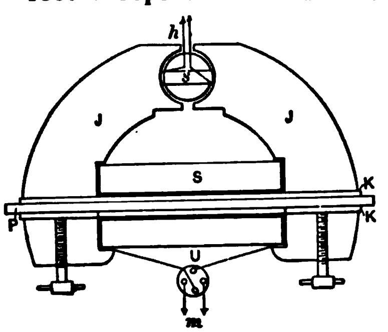

FIG. 150. A cross-section of the Koepsel permeameter.

current from a small auxiliary dry battery; deflections are indicated by a pointer on the dial (Fig. 152); the scale is calibrated directly in magnetic densities B per sq. cm.

U in Figs. 150 to 152 is a double-throw switch for reversing the current in the magnetizing coil S; W_m in Fig. 152 is a rheostat for regulating the current in the same coil. W_h is a rheostat for regulating the current in the moving coil; it has three handles, for coarse, medium and fine adjustment. S_1 and S_2 in Fig. 151 are compensating coils con-

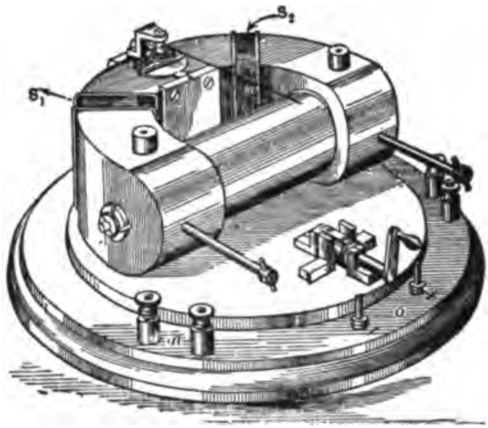

FIG. 151. The Koepsel permeameter, with the cover off.

nected in series with S and opposing it magnetically. These coils are adjusted so that the instrument shows zero, when the sample is taken out;

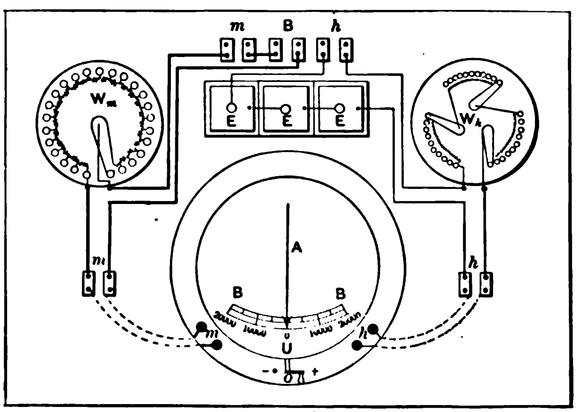

FIG. 152. The electrical connections in the Koepsel permeameter.

in other words, they compensate for the magnetic action of the coil S itself. In this way the apparatus is made to indicate directly the magnetic induction due to the sample under test.

The apparatus is intended for taking complete magnetization curves, similar to one shown in Fig. 138. The values of B are read off directly on the scale (Fig. 153) when the current i in the moving coil is adjusted to a value given on the instrument. This current $i = k \div q$, where k is an instrument constant, and q is the cross-section (in sq. cm.) of the sample under test. The smaller this cross-section, the smaller the flux, and the larger must be the current in the moving coil, in order to produce the same deflection.

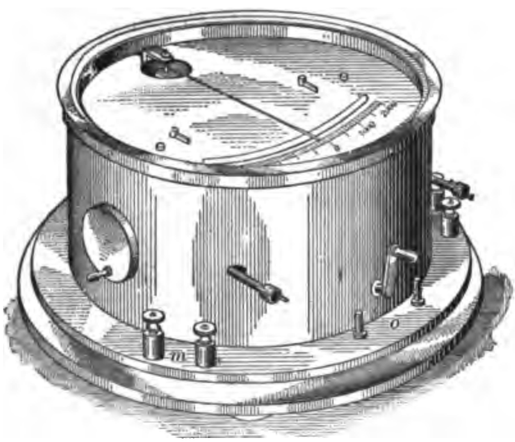

FIG. 153. The Koepsel permeameter.

The exciting ampere-turns are obtained by multiplying the current I in the coil S by its number of turns. The apparatus, as it is manufactured now, has 79.6 turns per cm., so that the exciting ampere-turns per cm. length of sample are $= 79.6\ I$. This is done in order to make the instrument direct-reading for magnetic densities H in the air (§ 145). Namely, from the formula (1),

$$H = \frac{nI}{0.796\ l} = \frac{79.6\ I}{0.796} = 100\ I.$$

There is no reason, however, why the instrument should not be made with 100 turns per cm., or per inch, so as to be direct-reading for ampere-turns per centimeter, or per inch.

The use of this apparatus is extremely simple: a sample of known cross-section is put into it, and the auxiliary current adjusted according to the formula $i = k \div q$; the value of k is given on the instrument itself. Then the main current is closed through the magnetizing coil, and simultaneous readings taken on the ammeter in the primary circuit, and on the dial of the apparatus. Ammeter readings multiplied by 79.6 give exciting ampere-turns per cm. (or, multiplied by 100, give values of H). The value of B is read off directly on the scale of the apparatus. By varying the current in S a complete B-H curve of the sample can be obtained.

Care must be taken to protect the apparatus from external magnetic fields; strong magnets, or large pieces of iron, should not be allowed near it, while readings are taken. The sample itself must have no long ends sticking out of the yoke, as they produce a stray field. The apparatus is sensitive even to terrestrial magnetism; in order to eliminate this error the device must be placed so that the line marked on the dial is in the direction "north-south." When the instrument is in this position and both currents are "on," the pointer must remain on zero, so long as there is no test sample in the apparatus.

There is in this, as in some other devices, a source of error, which is difficult to eliminate, namely, imperfect contacts between the yoke and the rod under test. The result is, that it takes more ampere-turns to produce a certain flux than it would without these unavoidable air-gaps; consequently, the apparent permeability comes out lower than it is in reality. An air-gap only 1/1000 of an inch long is equivalent in its magnetic resistance to nearly ½ inch of a good iron rod; therefore, when accurate results are required, the experimentally observed B-H curve must be properly corrected. Correction curves are usually supplied with the apparatus.

161. EXPERIMENT 7-D. — Magnetization Curves of Iron with Koepsel Permeameter. — Test a steel specimen, a cast-iron specimen, and a bunch of iron laminations. Special clamps are provided with the instrument for accommodating round and rectangular samples. Set the instrument in the N-S direction; see that the needle shows no deflection, without the sample, and with both currents on. Insert the sample, and demagnetize it (§ 147); use the commutator shown in front in Fig. 151 for reversing the current. Take the curves shown in Fig. 138. Correct the data obtained, in accordance with the standardization certificate of the instrument. Investigate the apparatus as to its sensitiveness to stray magnetic fields, to the influence of terrestrial magnetism, and to large iron masses in its proximity.

Report. Identical with § 159.

162. Esterline Permeameter. — The apparatus devised by Prof. J. W. Esterline for testing permeability is essentially a small direct-current generator; the sample to be tested completes the magnetic circuit of the machine. The working principle of the device may be understood with reference to Fig. 150, if the moving coil s be replaced by a regular direct-current armature driven by a motor. The magnetizing coil S, the sample P and the pole-pieces J, J are essentially the same as in the Koepsel permeameter. The flux in the sample, instead of being measured by a deflection of the moving coil s, is measured by the voltage

induced in the revolving armature. The magnetic density is figured out from the formula

$$\text{density} = \text{const.} \times \frac{\text{volts}}{\text{speed}}.$$

This follows from the fact that the voltage induced in the revolving armature is proportional to the flux and to the speed of rotation. Compensating coils are used to account for the reluctance of the air-gap and of the parts of the circuit, other than the bar under test.

In the apparatus as it is now manufactured, the exciting ampere-turns are varied by changing the number of turns in the magnetizing coil. There is no reason, however, why this should not be done by simply regulating the current in the coil by a suitable resistance, as in the Koepsel permeameter. The Esterline apparatus is substantially built, is not affected by terrestrial field, and is designed so as to be suitable for ordinary commercial work. It is claimed that an inexperienced operator, with hardly any knowledge of electricity and magnetism, can obtain accurate results after very little practice. The device is described in detail by the inventor, in the *Proceedings of the American Society for Testing Materials*, VI, 1906.

163. Ewing Permeability Bridge. — An ingenious method for comparing specimens of steel and iron to a standard sample was devised by Prof. Ewing (Fig. 154). S is a standard rod whose magnetization curve is known; T is the sample under test. Both are surrounded by magnetizing coils and are clamped in heavy iron yokes $P\,P$. The magnetic circuit is closed as shown by the arrows. The standard sample is excited with a certain number of ampere-turns; the number of ampere turns on the sample under test is varied until the fluxes in both samples become equal. This moment is recognized by the pivoted-magnetic needle m returning to zero. When the fluxes in the two samples are different, some lines of force must find their path through the horns $H\,H$ and the

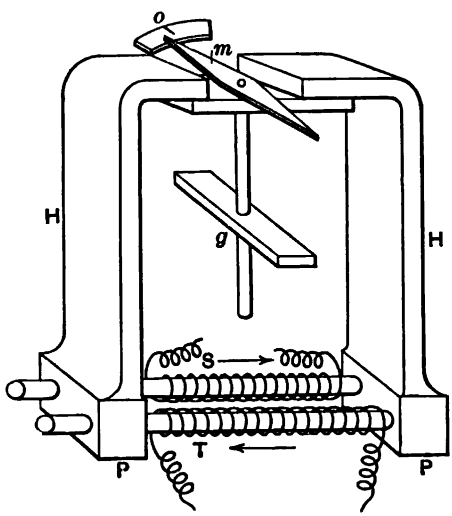

FIG. 154. The Ewing magnetic bridge.

air-gap between them, deflecting the needle. When the fluxes become equal, no stray flux passes through HH, and the needle returns to zero, under the influence of the permanent magnet g.

In the apparatus, as it is actually made, the number of turns around the standard sample S is fixed, that around the specimen T may be varied by a radial arm and contacts. A double row of contacts is provided, so that when a section of the coil is cut out of the circuit, an equivalent resistance is inserted in its place. This is done in order to maintain a constant current. The two magnetizing coils are connected in series, so that the ratio of active turns gives directly the ratio of ampere-turns. With this arrangement one ammeter is used instead of two.

The magnetization curve of the sample under test is plotted by changing the abscissæ of the magnetization curve of the standard sample. Let, for instance, the standard sample require 80 ampere-turns per inch at a density of 100 kilo-maxwells per sq. inch. Send through the magnetizing coils a current, such as to produce 80 ampere-turns per inch in the standard sample; adjust the number of turns of the specimen under test, until the needle m returns to zero. Let the number of turns in the standard coil be 100, that on the other coil 150. This shows that in order to obtain a density of 100 kilo-maxwells in the sample under test

$$80 \times \frac{150}{100} = 120$$

ampere-turns per inch are required. A calibration curve is usually furnished with the instrument to account for air-gaps.

The apparatus is called a "bridge," because of its resemblance to the Wheatstone bridge; the two horns HH and the magnetic needle correspond to the galvanometer circuit of the bridge (§ 14).

164. EXPERIMENT 7-E. — Magnetization Curves of Iron with Ewing Permeability Bridge. — The apparatus is described in § 163. The conduct of the experiment and the requirements for the report are the same as in § 159.

165. Bismuth Spiral.—The metal bismuth has the peculiar property that its electrical resistance increases appreciably when it is placed in a magnetic field. Per cent increase in resistance is nearly proportional to the magnetic density of the field. The curve shown in Fig. 155 gives an idea of this increase for an average specimen of bismuth wire. This property of bismuth is utilized to some extent for measuring magnetic densities. Fine bismuth wire is made into a flat spiral wound non-

inductively, the wire being doubled back on itself. The winding is held rigidly between two thin pieces of mica. Such a spiral is placed in a field, of which it is desired to measure the flux density; its ends are connected to a Wheatstone bridge. From the increase in the electrical resistance of the bismuth wire, flux density is determined by using the curve shown in Fig. 155. Bismuth spirals used for measuring flux density in air-gaps of electrical machines, stray fluxes, etc., are provided with handles and with suitable terminals. For testing permeability of iron with a bismuth spiral, an apparatus similar to that

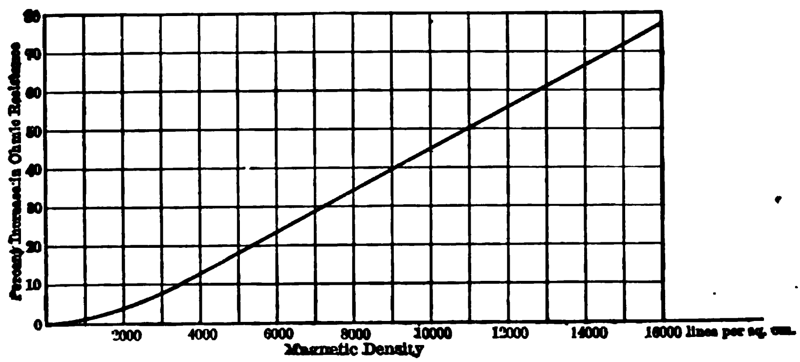

FIG. 155. Variation of resistance of a bismuth spiral in a magnetic field of varying density.

shown in Fig. 143 is used. The exploring coil E is omitted, and the spiral is inserted between the ends of the two samples T, T. Bismuth has an appreciable temperature coefficient; a correction must be applied for this factor when using the apparatus.

166. EXPERIMENT 7-F. — Magnetization Curves of Iron with Bismuth Spiral. — The method is described in § 165. The general conduct of the experiment and the requirements for the report are the same as in § 159.

NOTE TO PAGE 181: The deflection α depends largely on whether the galvanometer circuit is open or closed while the coil swings. If the circuit is closed, α depends also upon the resistance of the circuit; this resistance serves as an electromagnetic damper of oscillations. When the galvanometer is used for magnetic measurements, the galvanometer circuit is closed through an exploring or secondary coil. Therefore, when the same galvanometer is calibrated with a standard condenser, a special discharge key must be used. This key is connected so that first, the condenser is discharged through the galvanometer, and, immediately after (before the galvanometer coil has had time to move) the galvanometer circuit is closed through a resistance equal to that of the exploring coil. In some cases it is advisable to calibrate the galvanometer with a wide range of resistances.

CHAPTER VIII.

MEASUREMENT OF CORE LOSS.

167. Steel and iron cores used in armatures of electrical machines and in transformers are subjected to a variable magnetization. Each particle of the core is regularly magnetized in one and then in the opposite direction many times a second, according to the frequency of the supply or the speed of the machine. Under such conditions cores are appreciably heated; this heating is objectionable from two points of view:

(1) The temperature may reach a limit where it is dangerous to the insulation of the windings.

(2) The efficiency of the machine is lowered, by the amount of energy thus converted into heat.

An investigation of this heating of iron, and of the resultant loss of energy, shows that it is due to two distinct and independent causes: (1) molecular friction, or hysteresis; (2) induced eddy currents.

168. Physical Nature of Hysteresis. — The phenomenon of hysteresis is described in § **144**; as is stated there, flux density in iron lags behind the exciting ampere-turns, when it is subjected to cyclic magnetization. The accompanying loss of energy is probably due to some friction among the molecules of iron, when the magnetizing force causes them to be arranged along certain lines. A certain amount of energy is necessary to take one pound of iron through one cycle of magnetization up to a certain flux density. The loss of power depends therefore upon the *number of cycles* per second, in other words, on the frequency of magnetization. This power also increases with the *maximum flux density* to which magnetization is carried.

Thus hysteresis loss $W = \eta V f . F(B)$ watts, where V is the volume of iron, f the frequency of magnetization in cycles per second, $F(B)$ a function of the magnetic density, and η a physical coefficient, which depends on the quality of iron. Dr. Steinmetz found by extensive tests that hysteresis loss increases *on the average* as the 1.6th power of the density B. Accordingly, for many practical purposes it is assumed that

$$W = \eta V f . B^{1.6} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

In stationary machinery, as, for instance, in transformers, the energy necessary for overcoming this loss is supplied electrically, in the form of an additional component of the magnetizing current. In generators, hysteresis causes an opposing torque between the armature and the field; the energy for overcoming this torque is supplied by the prime mover. In motors the loss may be supplied from the line, or it may be considered as reducing the useful torque available on the shaft.

It is interesting to note that the counter-torque caused by hysteresis is independent of the speed of the machine. Let this torque be T foot-pounds and the speed of the machine n r.p.m. The power necessary for overcoming this torque is proportional to the product "torque times speed," so that

$$W = KnT \text{ watts},$$

where K is a numerical constant. Equating this expression to (1), we have

$$KnT = \eta Vf.B^{1.6}.$$

The number of cycles of magnetization f is proportional to the speed n of the machine, so that we finally get

$$T = K'\eta VB^{1.6}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where K' is another constant. This equation (2) shows that the torque caused by hysteresis does not depend on the speed of the machine.

169. Physical Nature of Eddy Currents. — Iron is not only a magnetic conductor but also a good conductor for electric currents. Therefore, when a magnetic flux varies in iron, currents are induced in it as in any other conductor subjected to a pulsating flux. These currents are called eddy currents, or Foucault currents, after a French physicist of that name; they constitute a pure loss of energy. To reduce these currents as far as possible, iron is used in the form of thin sheets, or laminations, insulated from each other by paint, varnish, tissue paper, etc., in order to break up the paths of eddy currents. For many practical purposes, iron oxide, usually formed on the surface of laminations during the process of annealing, is considered to be a sufficient insulation against eddy currents. Like all induced currents, eddy currents are proportional to the flux density B and to the frequency f of pulsations. Thus eddy currents per cubic unit of iron are proportional to the product Bf; the corresponding loss in watts is proportional to the square of the currents (according to the expression i_2r). Thus, we have

$$\text{eddy-current loss } w = \xi\, Vf^2B^2 \text{ watts} \quad . \quad . \quad . \quad . \quad (3)$$

The physical coefficient ξ depends on the thickness of laminations, and decreases approximately as the square of the thickness. Proceeding as in § 168, we find that the torque caused by eddy currents is

$$t = k'\xi VnB^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

This torque is proportional to the speed of rotation, or to the frequency of magnetization; it has been shown that the hysteresis torque (2) is the same at all speeds. This difference in the properties of hysteresis and eddy currents is utilized in practice for separating a loss caused by hysteresis from that due to eddy currents.

170. Methods for Measuring Hysteresis and Eddy Currents. — Core loss due to hysteresis and eddy currents lowers the efficiency and increases the temperature rise in machinery. It is important, therefore, to know how to measure this loss on samples of steel intended for use in electrical machinery. Results of core-loss tests are usually plotted in the form of the curves shown in Fig. 156. The curves give the total

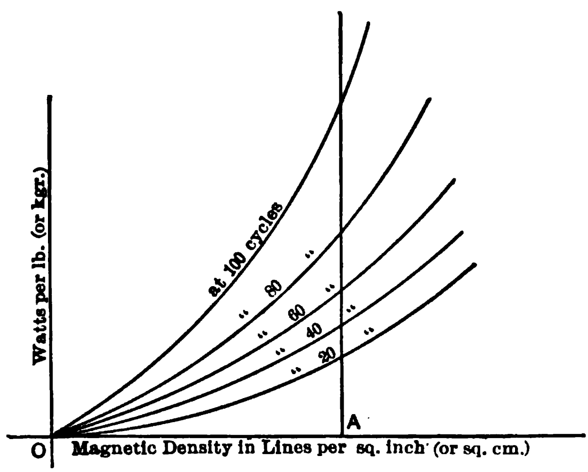

FIG. 156. Curves of iron loss at different magnetic densities and different frequencies of magnetization.

loss which comprises both hysteresis and eddy currents. In most practical cases it is not required to separate the two; but should this be necessary, it can be done as is explained in § 180.

Two distinct methods for determining iron loss are chiefly used: (1) Mechanical torque method, (2) Wattmeter method. With the

first method the samples to be tested are driven mechanically in a magnetic field (or vice versa), as if they were parts of the armature core of a generator. The torque produced by the core loss in the samples is measured by a dynamometer spring. With the wattmeter method samples are magnetized by an alternating current, as they would be in a transformer; the power necessary for magnetization is measured on a wattmeter.

The torque method should be used for sheet steel intended for armature cores of generators and motors; the wattmeter method is suitable for transformer iron. In practice, however, no such strict distinction is made between the two methods, because in most cases it is sufficient to know that a new lot of iron has a core loss not above a certain limit, set as the result of previous experience. It makes little difference in which way this limit is ascertained, provided the same method is used in cases to be directly compared.

A third possible method consists in integrating the area of a hysteresis loop of the sample (Fig. 138). It can be shown theoretically (see § 183) that the area of this loop is proportional to joules hysteresis loss per cu. cm. of iron, per cycle of magnetization. This method is seldom used, because it is rather lengthy; besides, it gives hysteresis loss only, and not the total core loss.

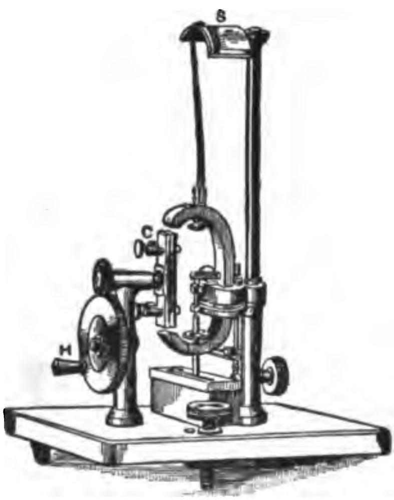

FIG. 157. The Ewing hysteresis tester.

MECHANICAL TORQUE METHOD.

171. Ewing Magnetic Tester. — This is the simplest and the oldest device based on the principle of measuring hysteresis loss by mechanical torque; it is shown in Fig. 157. A few strips of sheet iron to be tested are clamped into a carrier C, which is made to revolve by turning the handle H. The carrier turns between the poles of a permanent magnet, which is suspended on a knife-edge. In consequence of the hysteresis torque of the specimen the magnet is deflected, and the deflection is observed by means of a pointer on the scale S.

The same test is made with a standard sample, whose hysteresis

loss in watts per cycle has been previously determined by some other method (for instance, by integrating its B-H loop). The ratio of deflections gives the ratio of the values of hysteresis loss in the two samples.

The deflections of the pointer are practically independent of the speed of rotation; it is shown in § 168, equation (2), that hysteresis torque is independent of the frequency of magnetization. Yet, when the speed becomes rather high, the influence of eddy currents becomes noticeable, the deflection being thereby increased.

It must be noted, that the loss determined by this tester refers to a certain flux density only, and no provision is made in the apparatus for varying the density. The density within the samples is practically independent of the quality of iron tested; the value of the flux is chiefly determined by the reluctance of the two air-gaps. The instrument is adapted for rough relative tests rather than for determining absolute values of hysteresis loss.

172. EXPERIMENT 8-A. — Hysteresis Loss in Iron with Ewing Magnetic Tester. — Test a few samples of sheet steel and iron, as explained in the preceding article. Investigate the influence of the speed of rotation; make a sketch of the mechanical details of the device. Test one of the samples with laminations thoroughly insulated from each other, and then without insulation; see if the influence of eddy current makes itself perceptible in the second case. Form an opinion in regard to the accuracy of the instrument and its applicability for practical work.

173. Blondel Hysteresimeter. — This device (Figs. 158 and 159) is based on the same principle as the above-described Ewing magnetic tester, but is mechanically superior to it. It has a U-shaped permanent magnet MM which can be rotated around a vertical axis by means of the handle H. The sample sheets to be tested are made in the form of a ring R and are fastened on the support S. This support with its pivoted vertical shaft P, tends to revolve, but is retained by an opposing spiral spring, shown in the figure. When the magnet M revolves, the support with the sample turns by an angle, at which the

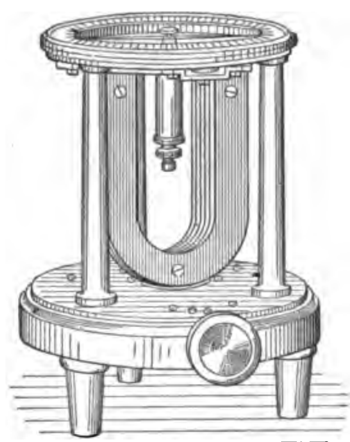

FIG. 158. The Blondel hysteresimeter.

hysteresis torque just balances the spring action. The deflection is practically independent of the speed of rotation, as in the above Ewing's apparatus, and is directly proportional to the hysteresis constant η of the sample (see § 168).

A standard sample, whose hysteresis constant has been determined by another method, is used with this instrument; the ratio of deflections

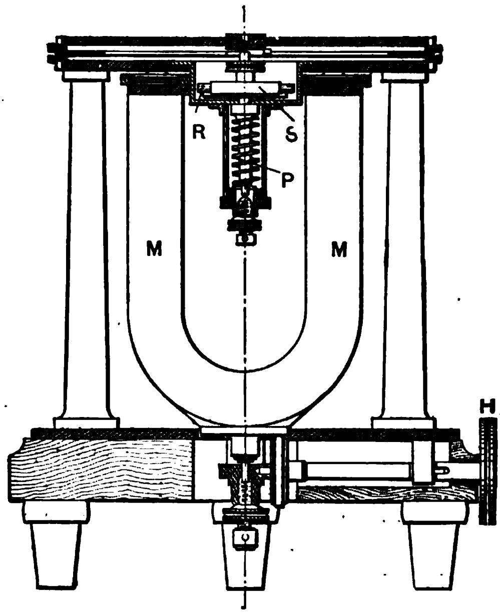

FIG. 159. A cross-section of the Blondel hysteresimeter.

given by the standard sample and the sample under test is equal to the ratio of their hysteresis constants.

The magnet M is selected of such a strength as to give in the sample a magnetic density B of about 10.000 lines per sq. cm. The reluctance of the air-gap is so large, as compared to that of the sample itself, that differences in permeability of different samples hardly affect the above value. Thus all samples are compared at a standard density of 10.000 maxwells per sq. cm.

In testing samples with this hysteresimeter it is always necessary to take readings with rotation both ways; the average of the two indications is the true zero position. This eliminates the error due to a possible previous magnetization of the sample.

To insert a sample into the apparatus, first remove the glass covering the scale, then take off the pointer and finally the support S. The

sample is clamped to the support, after which the parts are returned to their respective places. In performing the measurement it is advisable to rotate the handle at a speed of 2 to 3 revolutions per sec.

174. EXPERIMENT 8-B. — Hysteresis Loss with Blondel Hysteresimeter. — See directions for the preceding experiment (§ 172).

175. Holden-Esterline Core-Loss Meter. — The two above-described hysteresis testers are very simple and convenient to use, but they have the following disadvantages:

(a) Being rotated by hand, the frequency is so low that samples are tested for hysteresis loss only, while total loss is usually important.

(b) Hysteresis loss is determined at one density only.

(c) Readings are merely relative, so that a standard sample is required.

These objections are remedied in a device constructed by Mr. Frank Holden. In his instrument the magnetizing field is revolved by a

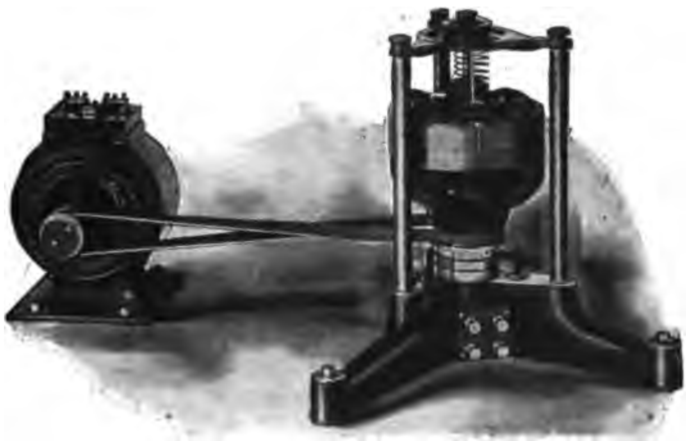

FIG. 160. Holden-Esterline core-loss meter.

motor at a required high frequency; moreover, an electromagnet is substituted for the permanent magnet, so that it is possible to test samples within a wide range of magnetic densities; the instrument is made to read the core loss directly in watts. Holden hysteresis meter is described in detail in Foster's *Pocketbook*. It has been somewhat improved by Prof. J. W. Esterline, and in this latter form is shown in Figs. 160 and 161.

The exciting field—with inwardly projecting poles, six in number — is made of stamped laminations, and mounted on a hub which can be rotated by means of a belted motor. The poles of this field are wound with exciting coils. For alternating-current work the frame

is left stationary; the coils are connected to a two-phase or three-phase circuit, so as to produce a rotating magnetic field.

The sample to be tested consists of concentric rings, mounted on a brass spider, whose shaft has a pivot below, resting on a jeweled

FIG. 161. Parts of the Holden-Esterline core-loss meter.

bearing. The upper end of the shaft is guided by a bearing in the dial plate. When the poles are rotated, or a rotating field produced by A. C. currents, the eddy currents and hysteresis in the sample tend to cause it to rotate also. It is, however, prevented from doing so, by a coiled spring, attached at one end to the spider which carries the sample core, at the other to a milled head on the dial plate. The pointer attached to the milled head is set at zero, when there is no twist in the spring. The angle of torsion necessary to turn the core back to zero, when the loss is taking place, is a measure of the loss.

Instead of calibrating the dial in ft.-lbs., or in gram-centimeters torque, it is calibrated directly in watts loss, at a certain standard frequency, for instance, 60 cycles per sec. At lower frequencies the readings must be accordingly reduced, at higher frequencies increased. The air-gap is made of sufficient length to make the flux density in the specimen practically proportional to the exciting current. Moreover, the permeability of the sample at the usual densities has very little effect on the flux in the instrument, so that the dial can be calibrated once for all. The apparatus is well adapted for commercial work; it is strong mechanically, and not much skill or electrical knowledge is required to operate it.*

* A somewhat similar device, in which the punchings are made to revolve and the field is stationary, is described by Mr. C. E. Skinner in the *Electric Club Journal*, 1904, p. 337.

176. EXPERIMENT 8-C. — Testing Iron with Esterline Core-Loss Meter. — For a description of the device see the preceding article. Test a few samples over a wide range of densities and frequencies; drive the field with a motor. Take a few readings with a revolving field produced by polyphase currents. Study the mechanical details of the apparatus; if possible, check the calibration of the dynamometer spring.

Report. Plot curves giving core loss in watts per pound of iron, at various densities and frequencies (Fig. 156). Separate hysteresis from eddy currents, as in § 180. Show the difference in the value of the loss with the field produced by polyphase currents; explain the discrepancy.

WATTMETER METHOD.

177. In the above-described core-loss testing devices the sample is subjected to "rotating hysteresis" as in generator and motor arma-

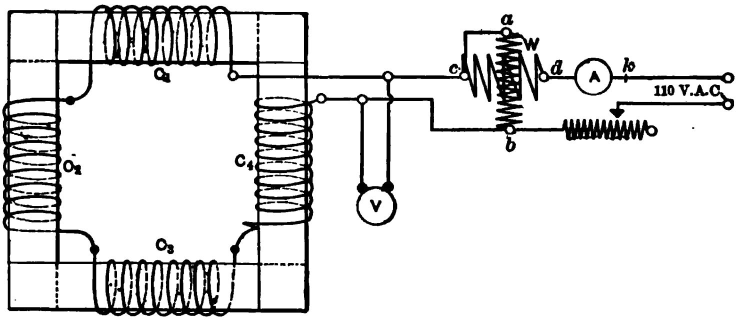

FIG. 162. Diagrammatic representation of the Epstein core-loss apparatus. See Note I on page 206 in regard to wattmeter connections.

tures. In transformers the iron core is subjected to so-called "alternating hysteresis"; in order to test samples under such conditions they are placed within coils excited with alternating current, and the magnetization loss determined by a wattmeter. The arrangement must be such as to have a closed magnetic circuit and at the same time not necessitate winding new magnetizing coils every time.

178. Types of Testing Devices. — Samples may be tested either in the form of rectangular strips or as stamped rings; some even prefer to test whole sheets as they come from the rolling mills. The devices described below are intended for testing iron in these various forms.

(a) *Arrangement for testing strips* (Epstein). The device shown in Fig. 162 is prescribed for core-loss tests by the German Institution of

Electrical Engineers; its details and dimensions may be found in their standardization rules (Vorschriften). The apparatus has four magnetizing coils, C_1, C_2, C_3, C_4, of a rectangular cross-section. Sample strips are inserted one by one; the ends in each two consecutive layers are overlapped as is shown by dotted lines. The four corners are clamped tight, so as to form practically a closed magnetic circuit. The coils

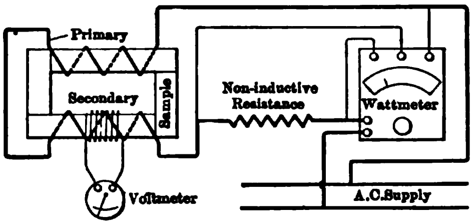

FIG. 163. Epstein arrangement improved by Esterline.

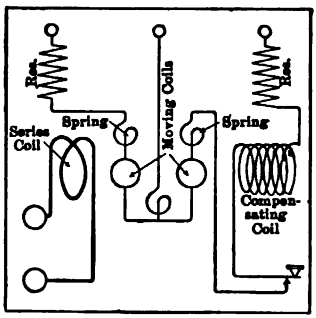

FIG. 164. Special wattmeter for use with the diagram of connections shown in Fig. 163.

are energized from an alternating-current supply having a wave-form as nearly sinusoidal as possible. Iron loss is read directly on the wattmeter W. The flux density in the iron is varied by varying the voltage at the terminals of the apparatus.

Prof. Esterline has improved the details of this method, as is shown in Figs. 163 and 164. The voltmeter is connected to a secondary winding, so that its readings are not affected by the resistance drop in the magnetizing coils C, but give directly voltages induced by the flux. The dimensions of the core and the secondary winding can be selected so that, for instance, 10 volts on the voltmeter correspond to a density of one kiloline per square centimeter (or per square inch).

The wattmeter is of special construction; the moving part has two

identical coils which oppose each other. One of these coils is connected across the magnetizing coils of the apparatus, while the other is connected across a non-inductive resistance equal to that of the magnetizing coils. Compensating coils are provided as in an ordinary instrument. The torque on one of the moving coils is proportional to the core loss plus the copper loss in the magnetizing coils; the torque upon the other moving coil is proportional to the copper loss in the non-inductive resistance, which is equal to the copper loss in the magnetizing coils. Thus, the wattmeter reading gives the net core loss in the sample.

(*b*) *Arrangement for testing whole sheets* (Richter). A narrow magnetizing coil is wound along the periphery of a barrel (Fig. 165), and whole sheets are shoved into it through the slot seen on top. The ends of the sheets are made to overlap each other, so as to form a closed magnetic circuit. The core loss at a definite voltage and frequency is determined by a wattmeter as in the two above-described devices. It is claimed that small samples, made from the same sheet, may show differences in core loss of over 10 per cent. Therefore, it is supposed to be more reliable to test complete sheets; besides, no time is lost in making samples.

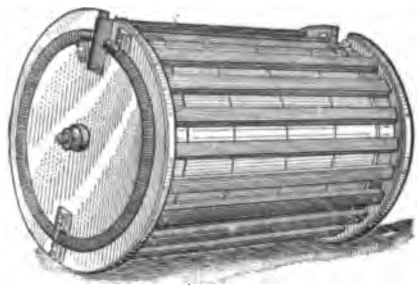

FIG. 165. The Richter drum for testing whole sheets of iron.

Instead of testing whole sheets, some manufacturing companies actually make transformer stampings of the material to be tested, build a regular transformer and determine its core loss.

179. Relation between Flux Density and Voltage. — The results of a wattmeter test on core loss are usually plotted in the form of curves shown in Fig. 156; the curves give watts loss to magnetic densities as abscissæ. These densities are figured out from the applied voltage E, number of turns s in the magnetizing coils, and the cross-section of the core under test. According to the fundamental equation of alternating-current apparatus the counter-e.m.f. e induced by the flux in the magnetizing coils is

$$e = \frac{2\pi}{\sqrt{2}} \cdot sfN \cdot 10^{-8} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

(see proof below), where N is the maximum value (amplitude) of the magnetic flux. Substituting in this formula AB in place of N, where

A is the net cross-section of the iron and B the density, also substituting for $2\pi \div \sqrt{2}$ its value 4.44, we get

$$e = 4.44\, sfAB \,.\, 10^{-8} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (6)$$

In this formula all the quantities can be measured directly, except the induction B and the counter-e.m.f. e. The latter is equal to the applied voltage E, less the ohmic drop in the magnetizing coils, see formulæ (7) and (8) below. Thus the only unknown quantity is B, which can thus be calculated.

Formula (5) is deduced as follows: The instantaneous value of the induced e.m.f., according to the fundamental law of induction (§ 118), is proportional to the rate of change in flux and to the number of turns connected in series; or

$$e' = s\frac{dN'}{dt} \,.\, 10^{-8},$$

where e' and N' are instantaneous values of counter-e.m.f. and flux. If the applied voltage varies according to the sine law, the flux must also follow the same law, so that

$$N' = N \operatorname{Sin} 2\pi\, ft.$$

Substituting we find

$$e' = 2\pi fs\, N \operatorname{Cos} 2\pi ft \,.\, 10^{-8}.$$

The counter-e.m.f. reaches its maximum at the moments, when ft = 0, 1, 2, 3, etc.; its value

$$\text{max. } e = 2\pi fs N \,.\, 10^{-8}.$$

Hence the effective value of the voltage

$$e = \frac{2\pi}{\sqrt{2}}\, sfN \,.\, 10^{-8},$$

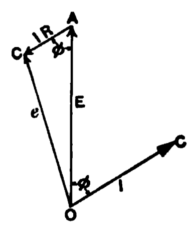

FIG. 166. Correction for the ohmic drop in the magnetizing winding.

which is identical with the formula (5).

In figuring out e from the applied voltage E it must be remembered that the ohmic drop IR has to be subtracted from E geometrically as shown in Fig. 166. OA is the vector of the applied voltage E, OB is the current I, which lags behind by an angle ϕ. This angle is known since

$$\operatorname{Cos} \phi = \frac{W}{EI},$$

where W is the wattmeter reading. Subtracting $AC = IR$ parallel to OB we get the counter-e.m.f. $OC = e$, which being substituted in formula (5) permits the calculation of B. Instead

of actually constructing the diagram, e can be determined analytically. Thus, from the triangle OAC we have, according to the familiar trigonometrical formula:

$$e^2 = E^2 + I^2R^2 - 2\,EIR \cos\phi;$$

substituting W in place of $EI \cos\phi$ gives

$$e^2 = E^2 + I^2R^2 - 2\,RW \quad . \; . \; . \; . \; . \; . \; . \quad (7)$$

In practice the power factor $\cos\phi$ is quite low; therefore the angle BOC, or ACO, may be assumed = 90 degrees. The triangle OCA becomes a right one, and we simply have

$$e^2 = E^2 - I^2R^2 \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad (8)$$

The correction in the form (7) must be used when ohmic drop is considerable; expression (8) is accurate enough for many practical purposes.

180. Analysis of Loss Curves. — The curves of total loss plotted as in Fig. 156 may be analyzed in two respects: (a) Hysteresis loss may be separated from eddy currents; (b) The laws may be determined according to which both losses vary with magnetic density.

(a) *Separation of hysteresis from eddy currents* is made on the basis of the fact that with a given density B hysteresis loss varies as the frequency f, while eddy-current loss varies as the square of the fre-

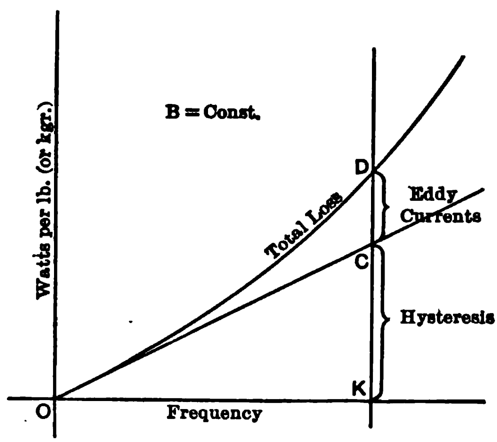

FIG. 167. Separation of hysteresis from eddy currents.

quency; see equations (1) and (3) in §§ 168 and 169. Let a density B be selected, such as OA in Fig. 156, and the values of total loss plotted to frequencies as abscissæ, — line OD in Fig. 167. If OC is drawn

tangent to OD near the origin O, the ordinates of OC represent watts hysteresis loss; the residue between OC and OD gives the eddy-current loss. It will be seen that the first increases directly as the frequency, the second as the square of frequency (the curve being a parabola). At low frequencies eddy-current loss is negligible, and practically the whole loss is due to hysteresis; this is the basis for the above construction. The same construction may be repeated for other values of B, and hysteresis loss separated from eddy currents throughout the entire range of the curves in Fig. 156. See also Note II on p. 206.

(b) *The exponent according to which hysteresis loss varies with the flux density* is determined in the following way: Assume the exponent of B in the formula (1), § 168, to be unknown. The formula may be written then in the form

$$W = aB^n,$$

where a is a constant with which we are not at present concerned. Taking logarithms of both sides of this equation, we get

$$\log W = \log a + n \, . \log B \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

This is the equation of a straight line with respect to log W and log B; the unknown exponent n is equal numerically to the trigonometric tangent which this line makes with an axis of abscissæ (Fig. 168). Thus, in order to determine n at a certain frequency, eddy-current loss must first be separated from the corresponding curve in Fig. 156. The rest is then replotted to a logarithmic scale, as in Fig. 168. It must give nearly a straight line; the slope of this line gives the exponent n.

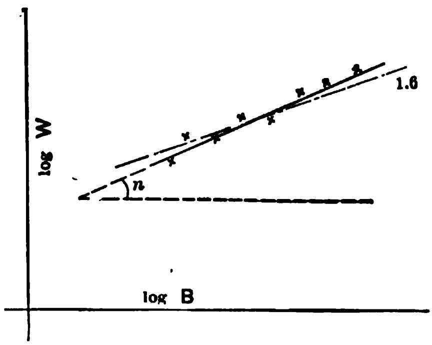

FIG. 168. Determination of the exponent according to which iron loss varies with the magnetic density.

It is convenient to plot this curve on a sheet of logarithmic paper. In this case, abscissæ and ordinates are obtained directly, without any calculation. Do not attempt to mark the origin; with the logarithmic scale it is at minus infinity. All that is needed is the slope n of the curve; this slope is independent of the position of the origin.

In some cases it may be desired to accept the exponent $n = 1.6$ as correct, and merely to find the value of a, in other words, of the constant η in formula (1). In this case a line having the slope of 1.6 is

drawn as closely as possible through the experimental points (Fig. 191). The coefficient a is then calculated for this line from the equation (9).

In a similar way, it may be checked that eddy-current loss increases as the square of magnetic density. Total core loss increases according to a power between 1.6 and 2. The corresponding exponent can be found by plotting the curves shown in Fig. 156 to a logarithmetic scale, without first separating hysteresis from eddy currents.

181. Magnetizing Current from Wattmeter Tests. — When performing a core-loss test by the wattmeter method, the data for the magnetization curve of the sample (Fig. 128) are incidentally determined. Let the wattless component of the current, in a test like the one shown in Fig. 162, be i_0. Let the number of magnetizing turns be s, and the length of the magnetic circuit l cm. The number of ampere-turns per centimeter length is a function of the density B; or

$$\frac{i_0 \sqrt{2} \, . \, s}{l} = F\,(B) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

The factor $\sqrt{2}$ is introduced because the ammeter measures the effective value of the current, while the density calculated from the formula (6) corresponds to the amplitude of the magnetic flux.

The value of magnetizing current is needed in practice for the determination of the no-load current of transformers, for which the iron under test is intended to be used. It is interesting to note, that the necessary excitation per pound of iron, at a certain density and frequency, may be given in "wattless" watts, instead of amperes. Namely, the cross-section A of the iron circuit, which enters in the formula (6), may be represented as $V \div l$, where V is the volume of the bunch of laminations. Thus we get

$$e = 4.44\, sf \, . \, \frac{V}{l} B \, . \, 10^{-8}.$$

Multiplying both sides of this equation by the magnetizing current i_0 we obtain

$$\text{magnetizing watts} = ei_0 = 4.44\, f \left(\frac{si_0}{l}\right) V \, . \, B \, . \, 10^{-8},$$

or,
$$\frac{\text{magnetizing watts}}{\text{per unit volume}} = \text{Const.} \times \left(\frac{si_0}{l}\right) . \, B \, . \, f$$

Substituting si_0/l from (10), and changing the constant in the ratio of the specific weight of iron, we get:

$$\frac{\text{magnetizing watts}}{\text{per pound}} = \text{Const.} \times f \times \text{function of } B.$$

This equation shows that it is possible to plot an *experimental* curve, which gives magnetizing watts per pound of sample at a standard frequency, as a function of magnetic density B.

This method of representing magnetizing current is very convenient in designing transformers, because the current can be figured immediately from the dimensions of the core. Or, else, the dimensions of the core may be determined under the condition that magnetizing current should not exceed a certain per cent of the full-load current.

182. EXPERIMENT 8-D. — Determination of Iron Loss by the Wattmeter Method. — Any of the devices described in § 178 may be used; the method is explained in § 179. Arrange the connections as in Fig. 162 (read Note I on p. 206); begin the test with B as high as 12,000 per sq. cm., and gradually reduce the voltage and the density down to zero. Read volts, amperes and watts. Repeat the same test with other frequencies, taking care to have as wide a range of frequencies as possible. Make a comparative test of iron loss with and without insulation between the laminations, in order to see the influence of eddy currents. Perform this test preferably at a high frequency, where the influence of eddy currents is more noticeable. Before leaving the laboratory measure the dimensions of the magnetic circuit and count the number of turns in the magnetizing coils. Measure the resistance of the windings; weigh the iron tested.

Report. (1) Plot curves of total loss as in Fig. 156; separate hysteresis from eddy currents as in Fig. 167 (or as per Note II on p. 206). Wattmeter readings must be corrected for copper loss; values of density B are calculated as in § 179. (2) Determine for one of the curves the exponent according to which the total loss, or the hysteresis loss alone, varies with the flux density (§ 180*b*). (3) Show by an example how to determine exciting ampere-turns per cubic inch at a given density. (4) Show how to apply the experimental data for obtaining a curve of magnetizing watts per pound of iron at a given frequency (§ 181); explain how to use this curve for figuring out the weight of iron in a transformer. The given conditions are: in a transformer of P kilowatts the magnetizing current should be not higher than p per cent of full-load current, and the core loss not greater than q watts per pound. (Give a numerical example.)

HYSTERESIS LOSS BY INTEGRATING B-H CURVE.

183. Hysteresis loss, in joules or watt-seconds, per cycle, per cubic unit of iron, is proportional to the area of the hysteresis loop (Fig. 138). The magnitude of the loss depends on the maximum magnetic density corresponding to the points M and M_1.

The proof is as follows: While iron is undergoing a cycle of magnetization, e.m.f.'s are induced in the exciting winding. The instantaneous energy supplied by the exciting circuit, or returned to it, is $ei.dt$, where i and e are instantaneous values of the exciting current and of the induced voltage; dt is an infinitesimal element of time. The total energy supplied during one complete cycle is

$$P = \int ie.dt \text{ joules.}$$

According to the fundamental law of induction we have

$$e = s\frac{dN}{dt}10^{-8},$$

where s is the number of exciting turns, N the instantaneous value of the flux. Substituting this value of e, we get

$$P = \int (si)\, dN \,.\, 10^{-8}.$$

The loss per cubic unit of the sample under test is

$$\frac{P}{Al} = \int \left(\frac{si}{l}\right) \cdot \left(\frac{dN}{A}\right) \cdot 10^{-8} \text{ joules,}$$

where A is the cross-section, l the length of the magnetic circuit. Referring to Fig. 138, the expression si/l represents magnetizing ampere-turns per unit length, or the abscissæ to which the hysteresis loop is plotted; $dN/A = dB$ is the differential of an ordinate of the same curve. Thus the above integral is reduced to the familiar formula of analytical geometry,

$$\int xdy,$$

which represents the area of a curve. If the sample undergoes f cycles of magnetization per second, we have hysteresis loss in watts per cubic unit $= f \times$ (area of hyst. loop) $\times 10^{-8}$. This method is very seldom used in practice for determining hysteresis loss, because:

(1) It is tedious, since it requires a complete magnetization curve to be taken and integrated for each point on the hysteresis loss curve.

(2) The iron is undergoing the magnetizing process slowly, while in actual machines it is magnetized and demagnetized many times per second. There are indications that hysteresis loss is somewhat different in the two cases.

(3) Eddy-current is not taken into account; in many practical cases the designer is interested to know not the hysteresis loss alone, but the total iron loss.

Nevertheless, the method is interesting from a theoretical and historical point of view; it is desired that the student integrate a loop in connection with one of the reports on the experiments 7-C to 7-F.

NOTE I, TO FIG. 162. When measuring iron loss by the wattmeter method, great care must be exercised in connecting up the ammeter, the voltmeter, and the wattmeter in such a way as to be able to calculate accurately the correction for the power consumption in the instruments themselves. Usually the correction amounts to several per cent; under unfavorable conditions it may be so large as to vitiate the results entirely.

With the connections shown in Fig. 162, a correction has to be applied for the power lost in the potential circuit of the wattmeter. Besides, the current in this circuit affects the ammeter reading, unless the potential circuit of the wattmeter is kept open when the ammeter is read. The voltmeter circuit must always be kept open when the ammeter or the wattmeter is read. On the other hand, closing the voltmeter circuit affects somewhat the voltage across the apparatus, though usually this effect is negligible.

Sometimes it is preferable to connect the end a of the potential winding of the wattmeter to some point k to the right of the ammeter, instead of to point c. In this case no correction is necessary for the power lost in the potential winding, but there is an appreciable correction for the I^2R loss in the ammeter and in the series coils of the wattmeter. The loss in the magnetizing windings, C_1, C_2, C_3, C_4, is conveniently included in this correction.

The author is of the opinion that no general rule should be given for instrument connections in the case under discussion, but that the student must exercise his judgment in each particular case, according to the range of the instruments used and their resistances. A few preliminary readings with two different wattmeter connections, and with the voltmeter circuit open and closed, will show him the best arrangement, that is to say, the one with which the correction is relatively the smallest, the most definite, or the one most easily taken into account.

NOTE II, TO § 180*a*. Besides the method given in § 180*a* for separating hysteresis loss from that caused by eddy currents, the method given in §§ 288 to 290 is also applicable, and, as a matter of fact, is more accurate. We have, analogously to formula (12) of § 288, for a certain constant flux density and a variable frequency,

Total iron loss, in watts per pound $= P = Hf + Ff^2$,

where f is the frequency, in cycles per second. H is the hysteresis loss *per cycle*; F can be called the eddy-current loss per cycle, with the understanding that this loss varies as the square of the frequency. The graphico-analytical solution explained in § 290 is the most convenient. Dividing both sides of the foregoing equation by f we get:

$$\text{Total loss, per pound, } \textit{per cycle} = P \div f = H + Ff.$$

This equation shows that a straight-line relation exists between $P \div f$ and f. Plotting the values of $P \div f$, calculated from the test results, against frequencies as abscissæ, a straight line is obtained corresponding to line DC in Fig. 236. When $f = 0$, the preceding equation gives $(P \div f)_0 = H$. Therefore, producing CD to its intersection with the axis of ordinates, we obtain $OA = H$. Knowing H, the coefficient F is determined as follows: Take an ordinate, such as MP; the part NP is equal to Ff; consequently, $F = NP \div f$. Having calculated H and F, the straight line of hysteresis loss (OC in Fig. 167) is constructed, being represented by the expression Hf; the parabola of eddy-current loss is plotted according to the expression Ff^2.

CHAPTER IX.

PHOTOMETRY OF INCANDESCENT LAMPS.

184. THE two important requirements of a good incandescent lamp are: high efficiency and long life. These requirements are to some extent contradictory, since high efficiency implies heating the filament to a high degree of incandescence; while, the higher the temperature, the shorter the life of the filament. Much effort has been devoted to obtaining higher degrees of incandescence than is possible with carbon, without unduly shortening the life of the lamp. The outcome of this has been the introduction of the carbon filament "graphitized" by a special process. Incandescent lamps provided with such filaments are known in the trade as metallized filament, or "Gem" lamps. Simultaneously with this, materials other than carbon have been tried; so far tungsten, tantalum and osmium filament lamps have been developed into commercial form.* To sum up the progress made in the last few years it is sufficient to state, that, — while the ordinary carbon filament lamp consumes at least 3.1 watts per candle-power and has an average life of not over 800 hours, — the tungsten filament lamp consumes only 1.25 watts per candle-power, has a life of about 1000 hours, and gives a better quality of light.

Instruments for measurement of *candle-power*, or luminous intensity of lamps, are called *photometers*; the science of measuring intensity and distribution of light is generally called photometry.

185. Principles of the Photometer. — The photometer, most widely used in practice for measuring candle-power of incandescent lamps, is illustrated schematically in Fig. 169; its construction may be understood by a consideration of Figs. 170 and 171. The lamp L_1 to be tested, and a standard lamp L_2 whose candle-power is known, are placed at the ends of a horizontal bar. This bar, or the photometer bench, as it is called, usually has a length of 100 inches or 250 cm. The lamps are brought up to their normal degree of incandescence, and a screen is placed between them. This screen is moved back and forth along the bar until it appears equally illuminated on both sides. According to the fundamental law of optics, the intensity of illumination decreases

* The Nernst lamp, with its filaments made of rare earths, also belongs to the class of incandescent lamps.

inversely as the square of the distance. Thus we have, when the intensity of illumination is the same on both sides:

$$J_1 \div J_2 = a^2 \div b^2 \quad . \; . \; . \; . \; . \; . \; . \; . \; . \quad \text{(A)}$$

where J_1 and J_2 denote the candle-power of the lamps in the horizontal direction, and a and b are their distances from the screen. If J_2 is known, J_1 can be calculated.

In order to understand clearly the meaning of this formula, assume first, that both lamps are of the same candle-power; it is evident then that they must be placed at equal distances from the screen in order to give an equal illumination. Now suppose that one of the lamps gives four times more light than the other; it must then be placed at a

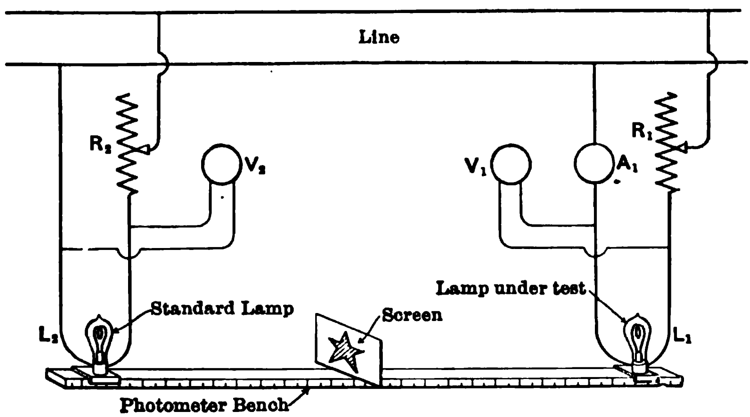

FIG. 169. Arrangement of parts in a photometer.

double distance from the screen in order to give the same illumination. If the lamp is nine times stronger, its distance from the screen must be three times greater than that of the other lamp. Conversely, knowing the ratio of distances at which two lamps give an equal illumination of the screen, the ratio of their candle-power may be calculated from formula (A).

The photometer screen, introduced in its simplest form by Bunsen, consists of a sheet of white paper, the middle part of which is made transparent by means of paraffine or stearine. The transparent spot is usually given the form of a star (Fig. 169), or a circle (Fig. 172). Such a "grease spot," when viewed by transmitted light, appears bright against a dark background, as shown in Fig. 172 to the right. On the contrary, when looked at by reflected light, the spot appears

FIG. 170. A standard photometer, with a Lummer-Brodhun sight box and other accessories.

darker than the rest of the paper, as is shown to the left. In a photometer the screen is illuminated simultaneously from both sides; the side illuminated stronger appears as shown to the left; the side which receives less light looks as is shown to the right. When illumination is the same on both sides, the grease-spot should disappear, as shown by the middle circle in Fig. 172. In reality, it does not disappear

FIG. 171. A portable photometer.

altogether, but a point is found where it is least visible, or where the contrast between the spot and the rest of the screen is the same on both sides. This position is that of an equal illumination; here the distances from both lamps are measured, and the luminous intensity of the lamp under test is calculated from formula (A).

186. Construction of a Photometer. — The screen described above

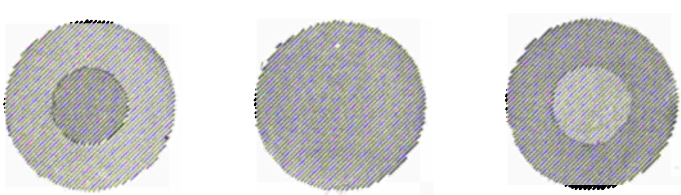

FIG. 172. Images visible on a photometer screen.

is placed in a "sight-box" (Fig. 173) which excludes all light, except that coming directly from the lamps under comparison. The box has openings for the rays of light coming from the two lamps, and an opening in front through which the observer may look. The box is shown with part of its walls removed, in order to illustrate its construction. It is provided with two mirrors, so that the observer sees both sides of the screen simultaneously. This makes the adjustment much quicker and more accurate, than if he had to look at the sides of the screen in succession. The sight-box is mounted on a rolling carriage (Fig. 170) or simply slides along the photometer bench (Fig. 171).

Of recent years, the so-called Leeson disk is coming into use, in place of the original Bunsen grease-spot. A star is cut out of a rather heavy paper, and is pasted between two sheets of thin paper. When viewed by transmitted light, the star naturally appears darker than the rest of the paper. When viewed by reflected light, the star looks lighter than the background, because it reflects more light. The setting is the same as with the original Bunsen photometer. The sight-box shown in Fig. 173 is provided with a Leeson disk; in the position illustrated, the screen is too near the lamp, to the left, making the action of that lamp preponderant. The sight-box should be moved to the right, until the two images in the mirror become identical, though the star does not disappear altogether with any setting.

The necessary electrical connections are shown in Fig. 169. Each

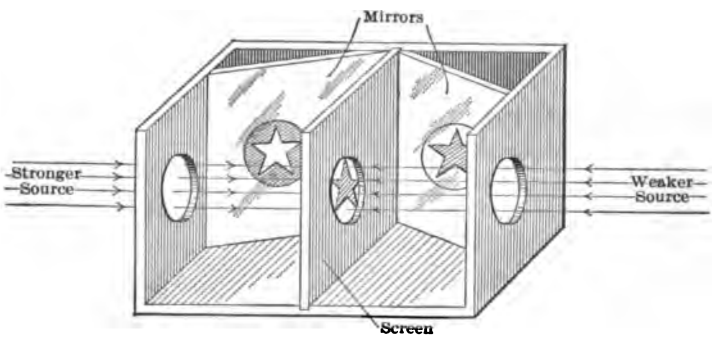

FIG. 173. A Bunsen sight-box.

lamp is provided with a rheostat and a voltmeter. The latter must be read very carefully, as the candle-power of the lamp depends essentially on the voltage at its terminals. An ammeter is provided in the circuit of the lamp under test, in order to be able to measure its power consumption. The rheostats are shown in Fig. 170 mounted on the columns which support the photometer bench; the measuring instruments are placed on the table.

In testing an incandescent lamp, it is usually rotated about a vertical axis, because the amount of light given in different vertical planes is different. The result thus obtained is called the *mean horizontal candle-power;* it is generally accepted in practice as the *rating* of an incandescent lamp. The lamp may be rotated either by hand or by an electric motor; a rotator is shown in Fig. 170 to the right; a universal rotator is illustrated separately in Fig. 174. The lamp should be spun at a speed of about 180 r.p.m.: at lower speeds, flickering is noticeable on the

screen; with higher speeds, the filament is deformed by centrifugal force and may break.

187. Standard Lamps. — The practical unit of luminous intensity in this country is the so-called "international" candle, also used in England and in France. It is defined as 100/90 of the German unit of luminous intensity.* The German unit of candle power, or the "hefner", is represented by a special lamp which burns a liquid called "amyl acetate." The dimensions of the lamp, the height of the flame, etc., are exactly specified, and the standard is reproducible with a considerable degree of accuracy. The name "hefner" was given in honor of the noted German electrician von Hefner-Alteneck, who developed the amyl-acetate lamp.

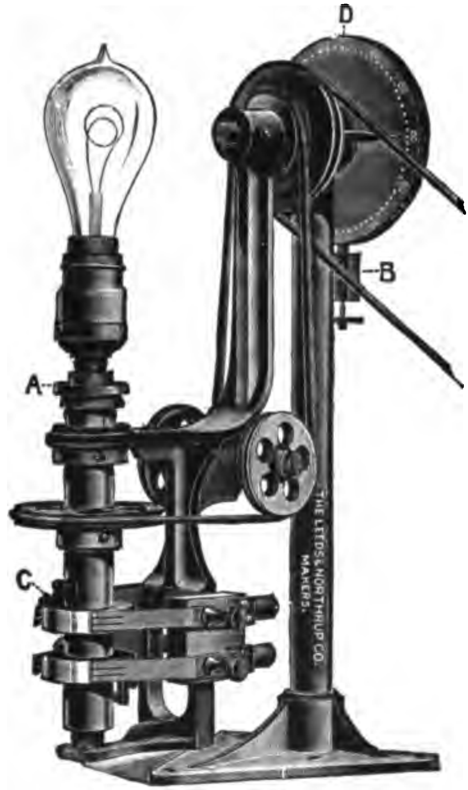

FIG. 174. The Willyoung universal rotator.

The amyl-acetate lamp is used at present as the primary standard only, for calibrating secondary standards. For secondary standards, well-seasoned incandescent lamps are used almost exclusively. An incandescent lamp selected to be standardized is first seasoned by burning say 100 hours, so that its candle-power becomes constant. Then it is compared (as in Fig. 170) with an amyl-acetate lamp, or with another incandescent lamp previously calibrated by means of it. The result of standardization is given in a form like this: the lamp gives at 106.7 volts 16 candle-power in the horizontal plane, and in a direction perpendicular to the plane of the filament; the current consumption is 0.523 ampere. The lamp must be used as a standard under these conditions only; it may be relied upon as long as the current remains the same at the stated voltage. When working for a long time, it is advisable to standardize temporarily

* The standard candle in use in the United States previous to April 1910 was equal to 100/88 of the German unit.

other lamps, and to check them from time to time against the first standard. It is customary also to have standard lamps in sets of three and to check them from time to time against each other.

One of the inaccuracies in measuring candle-power is caused by differences in color of the light given by the standard lamp and the lamp under test. The more pronounced the difference in color, the more difficult it becomes to find the correct position of the screen, that is to say such that the contrast is the same on both sides. It is advisable, therefore, to have several sets of standard lamps, calibrated at different

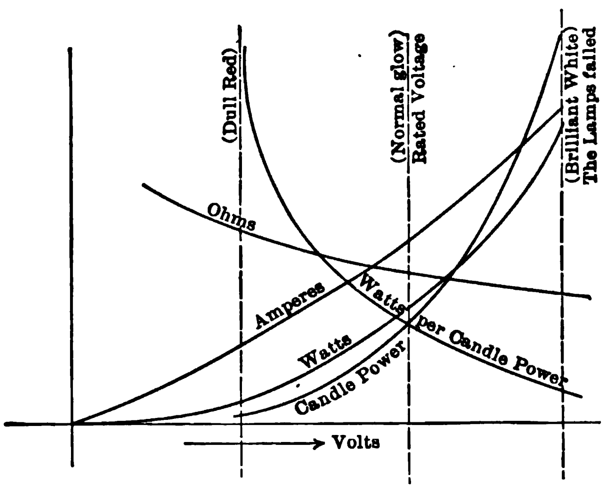

FIG. 175. Electric and photometric characteristics of an incandescent lamp, with varying voltage.

degrees of incandescence. In testing a lamp, a standard lamp is selected, the color of which is the nearest to that of the lamp under test.

188. EXPERIMENT 9-A. — Mean Horizontal Candle-Power and Efficiency of an Incandescent Lamp, with varying voltage. — The apparatus is arranged as in Figs. 169 and 170. The standard lamp is used during the test at its rated voltage; the voltage of the lamp under test is varied in steps, from the point where the lamp just begins to glow up to the voltage at which it burns out (Fig. 175). At each step the position of photometric balance of the sight-box is read, also volts and amperes. In setting the sight-box, do not move it back and forth too long trying to find the most accurate position of balance. This tires the eyes, and the accuracy of setting is impaired rather than

increased. Two photometer readings must be taken with each voltage, the screen being reversed for the second reading. This is necessary because the two sides of the screen may not be identical. The average of the two settings is taken as the true reading. The lamp should be rotated in vertical position during the test (Fig. 174), at a speed of about 180 r.p.m.

All outside light must, of course, be excluded, and the window-shades drawn. A small lamp operated with a push-button is convenient for reading the scale. Up to a very recent time, it has been considered necessary to have the walls of a photometer room painted black, to keep down stray reflected light. Mr. E. P. Hyde * showed conclusively, however, that this precaution is not necessary, if vertical screens of black velvet are placed on the photometer bench, in such positions as to make it impossible for reflected light to get into the sight-box.

When reading the ammeters, have the voltmeter circuit open, so as not to read the current flowing through it; otherwise a correction must be made, as in § 2. When reading volts, mark also the quality of light of the lamp under test: dull red, yellow, white, etc.

Report. Plot to terminal volts as abscissæ, the curves shown in Fig. 175. Candle-power is figured out from sight-box settings, by means of the formula (A). Let, for instance, the bench be 300 cm. long between the centers of the lamps, and let the balance be obtained at the division 120, counting from the standard 16 candle-power lamp. The distance from the lamp under test is (300–120) cm.; as the candle-power is inversely proportional to the square of the distances, we have for the candle-power of the lamp under test:

$$16\left(\frac{300-120}{120}\right)^2 = 16 \times 2.25 = 36.$$

Tables are available which give the ratios of distances squared for various settings of the screen, so that the calculation is much simplified. Some photometers have a scale calibrated in candle-power (Fig. 171); the scale is direct-reading if a 16 candle-power standard lamp is used for comparison; otherwise the reading must be correspondingly increased or reduced.

Plot first the curves of candle-power and amperes; amperes multiplied by volts will give the watt-curve. After this the curve giving watts per candle-power may be plotted. Ohms are calculated as a ratio of volts to amperes. State in how far the difference in color of the two lamps affected the accuracy of photometer readings.

* See *Bulletins of Bureau of Standards,* Vol. 1, No. 3, p. 417.

189. Life and Efficiency of Incandescent Lamps. — An inspection of the curves in Fig. 175 shows that the efficiency of an incandescent lamp increases with the voltage at its terminals; in other words, watts input per candle-power decreases. It may be stated here, that the latter expression is called *the specific consumption of the lamp;* some prefer to use its reciprocal (candle-power per watt) which is called the *efficiency of the lamp.* The use of the term "efficiency" is to be considered as special in this case, and should not be confused with per cent efficiency, as ordinarily applied to machinery.

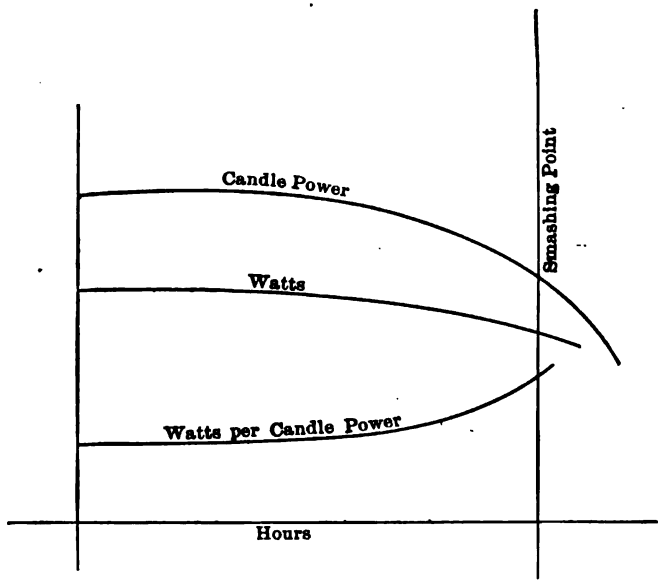

FIG. 176. Decrease of candle-power of an incandescent lamp with hours of service.

It is desirable to use lamps at as high an efficiency as possible, provided their life is not thereby shortened beyond a certain limit. For each class of incandescent lamps, there is a limit, above which an increase in efficiency is more than outweighed by a shortened life, causing an additional expense in renewals. The *useful* life of an ordinary carbon-filament lamp is considerably shorter than its *total* life (until the filament is burned out). This is illustrated in Fig. 176. After a certain number of hours of burning, the candle-power of the lamp begins to drop, chiefly on account of the bulb becoming blackened on the inside. The filament also becomes thinner, its resistance increases, and the power

taken by the lamp decreases. But the decrease in candle-power is much more pronounced than the decrease in power consumption; the result is, that the specific consumption, or watts per candle-power, is gradually increasing. At a certain point, say where the candle-power is reduced to about 80 per cent of the original, it is usually cheaper to discard the lamp and to buy a new one, than to pay for an increased specific consumption. This point is called the "smashing" point of the lamp. Methods have been developed for replacing filaments, so that lamps are no longer "smashed" but sold to factories making a specialty of renewing them. To renew the filament, the bulb is opened at the tip and the old filament taken out; then the bulb is washed out, and a new filament inserted in place and soldered to the leads. The air is again exhausted, and the tip sealed.

Ordinary carbon-filament lamps may be had with a specific consumption of from 3 to 4 watts per mean horizontal candle-power. The value of the specific consumption is selected according to the purpose for which the lamp is to be used, and with regard to the cost of power. Low-efficiency lamps have a longer life, are less sensitive to voltage fluctuations, but consume more power, and give a yellowish light. High-efficiency lamps require a very good voltage regulation, or their life is much shortened; they are more economical, and give a light more closely resembling daylight. The *tungsten* lamp, which seems to be the incandescent lamp of the future, not only has a much lower power consumption than the carbon-filament lamp, but it preserves its candle-power better until the filament is burned out. In addition to this, the tungsten lamp is less sensitive to voltage fluctuations, because the resistance of tungsten increases with temperature.

Lamps are tested and rated in factories according to their voltage, candle-power, and specific consumption. It is not sufficient to determine that a lamp gives 16 candle-power at 110 volts; its specific consumption per candle-power must be near a desired figure, say 3.5 watts; if it is different, the lamp is allotted to another class. For such measurements, involving a simultaneous determination of candle-power and of specific consumption, Messrs. Hyde and Brooks have developed an ingenious "Efficiency Meter for Incandescent Lamps." The arrangement consists in the combination of an ordinary photometer and an indicating wattmeter. A variable resistance is connected into the potential circuit of the wattmeter, and is regulated automatically by the movement of the sight-box carriage. The adjustment is such, that with a standard 16 candle-power lamp, the wattmeter reads directly the specific consumption of the lamp under test when photometric balance is obtained. At the same time the candle-power of the lamp

is read on the photometer. The device will be of convenience in places where a large number of lamps are regularly tested, rated and assorted. For details of this apparatus see *Bulletins of the Bureau of Standards*, Vol. 2, No. 1, p. 45.

190. EXPERIMENT 9-B. —Influence of the Blackening of the Bulb on Candle-Power and Efficiency of Incandescent Lamps. — The useful candle-power of incandescent lamps decreases with time, due to the bulb being gradually blackened on the inside by a deposit of the material of the filament. It would not be expedient to test in the laboratory lamps blackened during the regular service, as it takes several hundred hours to produce an appreciable effect. To show the student the blackening effect, it may be obtained in a few minutes by subjecting the

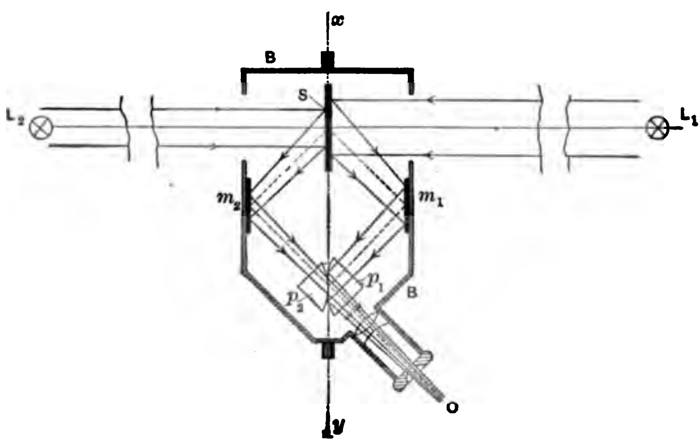

FIG. 177. The path of rays in a Lummer-Brodhun sight-box.

lamp to an over-potential. Take a few new lamps and determine their candle-power at the rated voltage, as in § 189. Then subject each of them to various voltages above the normal and for different periods of time. When the current is turned off, the blackening is noticeable by holding a sheet of white paper behind the lamp. Get different degrees of blackening, and test lamps again for their candle-power and power consumption. This will give an idea of what takes place in a prolonged regular service at the normal voltage.

191. The Lummer-Brodhun Sight-Box. — This sight-box is shown on the carriage in Fig. 170; a horizontal cross-section of the same is shown in Fig. 177. It was expected by the inventors that a greater accuracy could be obtained with a purely optical combination than with a

grease-spot. Many practical photometricians claim, however, that nearly as good results, at least for ordinary purposes, are obtained with an ordinary Bunsen sight-box, especially if provided with a Leeson disk. At the same time, the Bunsen sight-box is considerably less expensive, and does not so much tire the observer's eyes, because both eyes are used simultaneously. As, however, the Lummer-Brodhun sight-box is used to a considerable extent for photometrical work of precision, and when the colors of the two lamps under comparison are different, a description of this sight-box seems not to be out of place here.

Two lamps under comparison, L_1 and L_2 (Fig. 177), illuminate an opaque diffusing screen S, whose coefficient of absorption is as low as possible. The light diffused from the two sides of this screen is reflected by the mirrors m_1 and m_2 and reaches the observer's eye at O through the prisms p_1 and p_2. In the better grade of instruments,

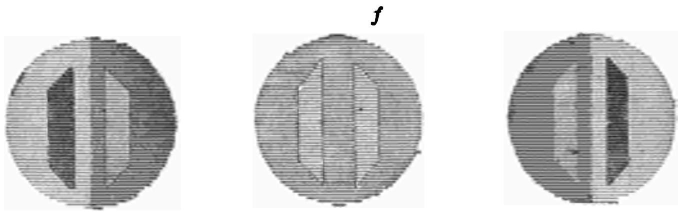

FIG. 178. Images visible in a Lummer-Brodhun sight-box, with a contrast attachment.

totally reflecting prisms are used in place of the mirrors m_1 and m_2. The prisms p_1 and p_2 are made of such a shape, that the observer sees the figure shown in Fig. 172. The inner circle corresponds to the light transmitted from the left side of the screen S; the outside circle is caused by the illumination of the right side of S, the rays undergoing a total reflection from the hypothenuse surface of p_1. The sight-box BB is moved along the bench until the difference in illumination disappears, as in the middle circle, Fig. 172; or at least is reduced to a minimum. To take into account a possible inequality in the diffusing power of the two sides of the screen S, the box may be turned by 180 degrees about the axis x-y, and a second reading taken.

The accuracy of setting is increased by using the so-called *composite sight field* (Fig. 178). The trapezoids visible in the field are caused by corresponding figures being cut out on the hypothenuse surface of the prism p_2. The left semicircle and the right trapezoid show the illumination of the left side of the screen S; the rest of the field is illuminated

by the light diffused from the right side of the same screen. The sight-box is moved along the bench until the field becomes as nearly as possible uniform.

When the lights to be compared are of different color, for instance, an incandescent lamp and a Nernst lamp, the figures in the sight field do not disappear with any setting. In such cases, the difference is artificially increased, by applying the so-called *contrast principle.* This is done by interposing thin strips of glass so as to slightly darken one-half of the beam of light from each source. The strips are placed on the prisms p_1 and p_2, on the sides exposed to the light. Under such conditions, the composite field appears as is shown in Fig. 178, all four parts being of different shade. When the illumination is balanced, the field appears as in the middle figure; the trapezoids do not disappear, but the *contrast* between them and the background is the same on both sides. The dividing line usually does not disappear altogether; in setting the screen, the observer should try to obtain an equal contrast on both sides, and not pay any attention to the dividing line. Lights of different color can be compared more accurately by this method than with a uniform sight field.

192. Flicker Photometer.—The contrast principle described above offers but a partial remedy in cases where there is a considerable difference in color between two lights to be compared. Thus most people would not be at all able to compare the greenish light of a mercury vapor lamp with a yellowish incandescent standard. Professor O. N. Rood was the first to point out that the accuracy of photometric comparison is much increased by examining the two surfaces of the screen in rapid succession, instead of simultaneously, as in the photometers described above. Photometers built on this principle are called *flicker* photometers; the principle may be understood with reference to Fig. 179. Let m_1 and m_2 be two identical mirrors mounted on the shaft s and rotated by the handle h. The mirror m_1 is mounted so as to give the observer the image of the lamp L_1; the mirror m_2 (when in the dotted position) gives the image of the lamp L_2. When viewing the revolving mirrors through a translucent screen, the observer receives alternate impressions from both lamps. When the speed of rotation is very low, he sees intermittent light; at very high speed the light appears continuous, because of the so-called persistence of vision. Between these two limits, there is a range of speed at which the light appears to flicker, without being completely extinguished. When the mirrors are rotated at this speed, the flickering is more pronounced, the greater the difference in the luminous intensities of the lamps under comparison. As the intensities become nearer each other, the flickering sensation

gradually disappears. Experiment shows, that the effect is to a large extent independent of the difference in color between the two lights.*

Various flicker photometers have been constructed on this principle: one of the latest is that by Franz Schmidt and Haensch (*Zeitschrift für Instrumentenkunde*, 1906, p. 249). The optical system in this photometer is such that when the revolving part is at rest, the field of vision appears as shown to the left in Fig. **172**. Turning one of the prisms of the system by 180 degrees changes the field of vision to that shown to the right; the lamp which gave the inside circle is now made to illuminate the outside circle. When the prism is revolved at the

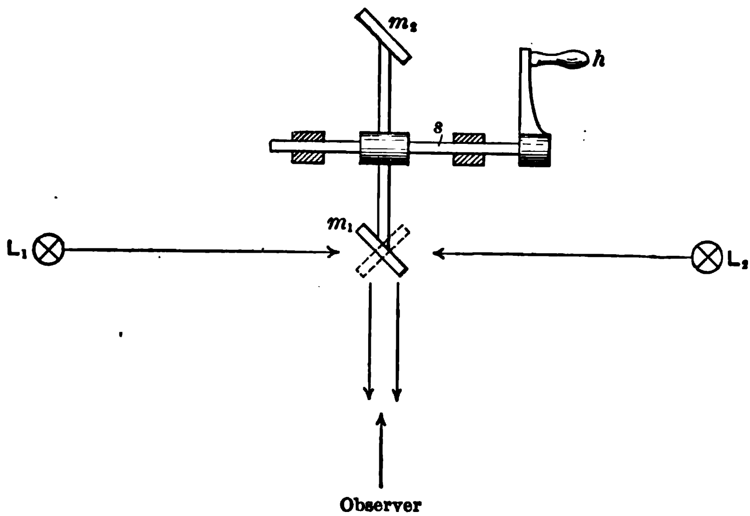

FIG. 179. **Essential parts of the flicker photometer.**

critical speed of flickering, the circles exchange their shades constantly, and a pronounced phenomenon of flickering is produced. The sight-box is moved until flickering disappears, and the whole field looks uniform, as in the central figure. It is important to have the right speed of rotation, particularly with lights of markedly different colors. The speed must be such, that when the setting is approximately correct, the field of vision appears in a uniform mixture of color of the two sources, and flickering is caused only by differences in the intensity of illumination. Then the final setting is made by reducing this flickering to a minimum.

* **In actual flicker photometers, diffusing screens are used in place of mirrors.**

It is claimed that with a good flicker photometer, lights widely different in color may be compared with nearly the same accuracy that lamps of equal color are compared with ordinary photometers.

193. EXPERIMENT 9-C. — Photometric Comparison of Lights of Different Color. — There is difficulty in comparing two lights of different color with an ordinary Bunsen photometer screen, since the screen does not appear equally illuminated on both sides in any position of the sight-box, — with the result that different observers are apt to give entirely different settings. Better results are obtained with the con-

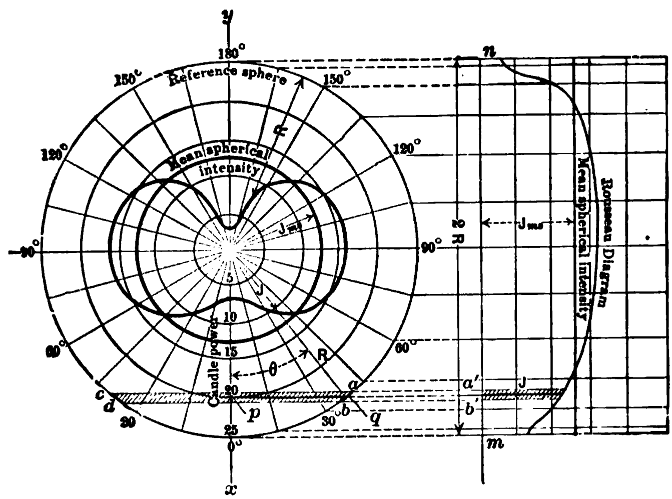

FIG. 180. Photometric curve of an incandescent lamp, and the corresponding Rousseau diagram.

trast photometer (§ 191), and still better with the flicker photometer (§ 192). The purpose of this experiment is to show the student the accuracy obtainable in various cases.

Take two incandescent lamps, bring them up to such voltages as to get nearly the same color of light; compare the lamps by means of an ordinary Bunsen screen, and determine per cent accuracy of setting. Now take two incandescent lamps having a markedly different color (different degree of incandescence) and determine the accuracy with which they can be compared with the same photometer. After this, compare lamps still more different, for instance a tungsten lamp and a carbon filament lamp. A still greater difference in color is obtained by taking in succession an arc lamp, a mercury vapor lamp,

etc., and comparing them with an incandescent lamp. In each case pay particular attention to the accuracy with which the setting can be made. Now repeat the same tests with a Lummer-Brodhun contrast photometer, and finally with a flicker photometer. You will find that considerably more accurate settings are possible with these devices.

DISTRIBUTION OF LIGHT AND MEAN SPHERICAL INTENSITY

194. An incandescent lamp gives different illumination in different directions. Differences are particularly pronounced in the vertical plane (Fig. 180). The radii of the oval curve give luminous intensities in the corresponding directions, the horizontal radius being equal to 16 candle-power. The form of the curve depends essentially on the form of the filament of the lamp.

Such a curve of distribution of light around a lamp may be obtained with an ordinary photometer, by having the lamp mounted on a universal rotator, such as shown in Fig. 174. The rotator is driven by a belt from an electric motor. The axis of rotation may be set at any desired angle with the vertical, in steps of 5 degrees. In this way the mean candle-power may be determined in any desired direction; the results plotted as radii give the curve shown in Fig. 180. Angles are read on the dial *D*. A positive pin-clutch *B* catches the frame of the rotator at each desired angle. The rotator has an additional pair of brushes *C* for voltmeter leads; in this way voltage is measured at the terminals of the revolving lamp, independent of the contact resistance of the main brushes.

195. Mean Spherical Candle-Power. — An examination of the distribution curve in Fig. 180 shows that a lamp rated at 16 candle-power in reality gives considerably less than 16 candles in directions other than horizontal. In many cases a lamp is intended to throw useful light downward; it will be seen that a lamp with a nominal rating of 16 candle-power gives only between 6 and 7 candle-power in the vertical direction (unless it is provided with a reflector). This fact is appreciated more and more by illuminating engineers, and a feeling is growing that lamps should be rated on the basis of their *mean spherical candle-power*, and not according to their mean horizontal or maximum candle-power. The mean spherical candle-power is indicated in Fig. 180 by a circle; it will be seen that it is only 13 candle-power instead of 16 candle-power.

The ratio of the mean spherical to the mean horizontal candle-power is called the *spherical reduction factor* of the lamp. In the case shown, the spherical reduction factor is equal to $13/16=0.81$.

Knowing the spherical reduction factor for a certain type of filament, the mean spherical candle-power can be calculated from the observed horizontal candle-power; this makes unnecessary taking a complete distribution curve.

Mean spherical candle-power may be determined in two ways:

(1) By calculation, from the distribution curve.
(2) By means of integrating photometers.

These two methods will now be considered more in detail.

196. Rousseau Diagram. — The mean spherical candle-power is calculated in the following way from the distribution curve shown in Fig. 180. Let J be the luminous intensity, or the candle-power of the lamp, in a certain direction. Imagine a sphere of radius R around the lamp and let ds be an infinitesimal element of the surface of the sphere. We then have

$$4\pi R^2 \,.\, J_{ms} = \int J \,.\, ds \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where $4\pi R^2$ is the surface of the "reference sphere," and J_{ms} is the unknown mean spherical candle-power of the lamp. The equation (1) expresses the condition that the actual "flux of light" is the same as if the intensity were uniform in all directions and were equal to J_{ms}. When the distribution curve is obtained with a rotator, each intensity J at an angle θ is the same for an infinitesimal zone of the reference sphere. The area of the zone is equal to its circumference times the width; thus

$$ds = 2\pi R \operatorname{Sin} \theta \,.\, R\, d\theta.$$

Substituting in (1) we get

$$4\pi R^2 \,.\, J_{ms} = \int_0^{\pi} J \,.\, 2\pi\, R \operatorname{Sin} \theta \,.\, R\, d\theta,$$

or

$$J_{ms} = \tfrac{1}{2} \int_0^{\pi} J \operatorname{Sin} \theta \,.\, d\theta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The mean spherical intensity J_{ms} may be calculated from this expression by dividing the distribution curve into small parts, say corresponding to 5 degrees, and summing up elementary products $J \,.\, \operatorname{Sin} \theta$. Let 180 degrees be divided into n parts; $d\theta$ must be replaced by a finite increment $\Delta\theta = \pi \div n$, and summation used for integration. We obtain:

$$J_{ms} = \frac{\pi}{2n} \sum_0^n J \operatorname{Sin} \theta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The expression (2) may also be integrated by means of a planimeter, if the distribution curve be replotted in rectangular coördinates, as shown in Fig. 180, to the right; this is the so-called Rousseau diagram. A vector, such as J, is produced to its intersection with the reference sphere; the point thus obtained is projected on the vertical axis of abscissæ of the Rousseau diagram, and the same J plotted as the ordinate. The mean ordinate of the Rousseau diagram gives directly the mean spherical intensity of the lamp. This can be proved as follows: The abscissæ of the new curve, counted from the middle point (latitude of 90 degrees), are equal to R . Cos θ; the ordinates represent the values of J. Thus, the area of the curve is

$$\int_0^\pi J \,.\, d\,(R \operatorname{Cos} \theta) = -\,R \int_0^\pi J \operatorname{Sin} \theta \,.\, d\theta.$$

This expression, save for the factor $2R$, is the same as formula (2). Thus, in order to find the mean spherical intensity, the area of the Rousseau diagram must be divided by its length $2R$. The process is evidently the same as in finding the mean ordinate of a curve; this proves, that mean spherical intensity is represented by the mean ordinate of Rousseau diagram.

197. EXPERIMENT 9-D. —Mean Spherical Intensity of an Incandescent Lamp from its Curve of Distribution of Light.— The lamp to be tested is mounted on a universal rotator (Fig. 174) and compared to a standard lamp by means of the photometer shown in Fig. 170. At first the lamp is rotated about a vertical axis; then the position of the axis is changed every five or ten degrees throughout the range of 180 degrees. After this, the rotator must be stopped, the lamp brought in its original position, and the luminous intensity determined in various meridians. As such, select the plane of the filament, the plane perpendicular to it, and a few intermediate vertical planes.

The same lamp should be tested with the bulb frosted. Frosting is done by dipping the lamp while warm into the so-called frosting compound (can be obtained from lamp-dealers). This gives only a temporary frosting, but is sufficient for the purpose; the compound can be washed off with alcohol. Permanent frosting is obtained by sand-blast or by dipping the bulb in hydro-fluoric acid. The same experiment may be repeated with a lamp having a decidedly different form of filament; also with tantalum, tungsten and Nernst lamps.

Report. Plot curves of distribution of mean luminous intensity in the vertical plane, as in Fig. 180; also curves of distribution of candle-

power in the horizontal plane. Figure out the mean spherical intensity for one of the lamps by means of the Rousseau diagram; for another lamp by using formula (3). Calculate the corresponding values of spherical reduction factor. Discuss differences in the distribution of light due to differences in the form of filaments.

INTEGRATING PHOTOMETERS.

198. The above procedure for determining the mean spherical candle-power, by taking a curve of distribution of light and integrating it, has the obvious disadvantage of being rather tedious for practical purposes. Considerable effort has therefore been devoted in recent years to the development of "integrating photometers," by means of which the mean spherical intensity of a lamp is determined in one reading. Of the various types of such photometers, two which are particularly suitable for testing incandescent lamps are here described. Some other types are described in § 219 in connection with photometering arc lamps.

199. The Matthews Integrating Photometer. — The device is shown schematically in Fig. 181, in elevation and in plan. The rays from the lamp L_1 under test are reflected by means of two sets of mirrors *mm* on an ordinary Bunsen or Lummer-Brodhun photometer screen. The screen is illuminated on the other side by the standard lamp L_2. The mirrors being placed along a semicircle, the screen is illuminated simultaneously by the rays of the lamp L_1 coming from different directions. The photometer screen is stationary; the standard lamp is moved along the bench until a photometric balance is obtained. The lamp under test is rotated on its vertical axis as in § 206. The setting gives directly the mean spherical intensity of the lamp under test, according to the formula

$$J_{ms} = \text{Const.}\ \frac{J_2}{D^2},$$

where J_2 is the horizontal intensity of the standard lamp, and D the distance between the standard lamp and the screen. The constant is determined experimentally by using a lamp L_1 whose mean spherical intensity has been previously determined by integration (§ **197**).

The following is the proof that the illumination on the left side of the photometer screen is proportional to the mean spherical intensity of the lamp L_1. According to equation (3) the mean spherical intensity consists of elementary products J. Sin θ, the mean illumination J of various zones being reduced, or "weighed" in proportion to the areas of the corresponding zones. This is exactly the reduction of illumina-

tion obtained with the disposition of mirrors in Fig. 181. The light from the mirror at a latitude of $(90° - \theta)$ is incident on the screen at an angle of $(90° - \theta)$. According to the so-called Lambert's law of optics, the illumination on a diffusing surface varies as the cosine of the angle of incidence. Therefore the illumination produced on the screen by the above mirror, is proportional to $J . \text{Cos}\ (90° - \theta)$, or to

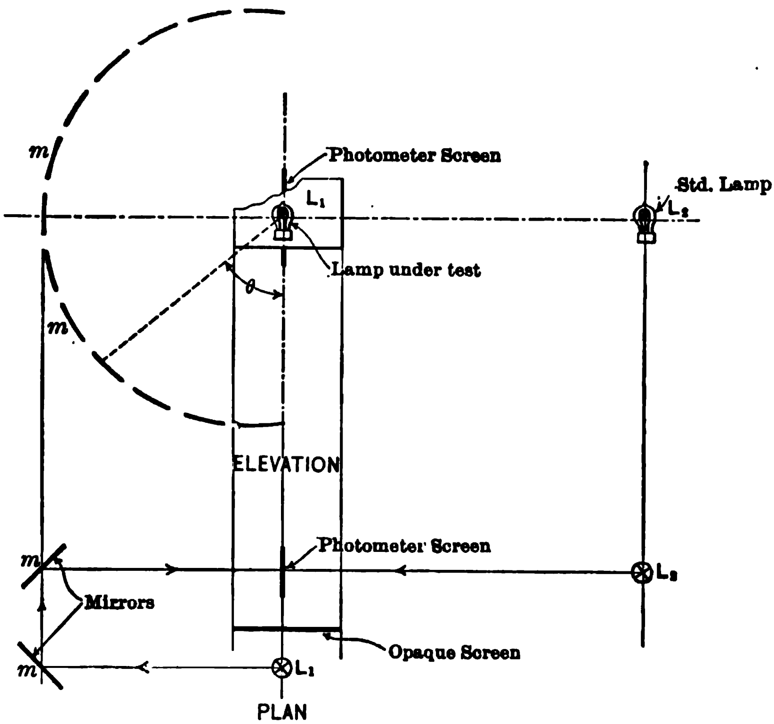

FIG. 181. The principle of the Matthews integrating photometer for incandescent lamps.

$J . \text{Sin}\ \theta$. Thus, the total amount of illumination from all the mirrors is proportional to $\sum J . \text{Sin}\ \theta$, or, according to equation (3), is proportional to the mean spherical intensity of the lamp.

200. Ulbricht's Integrating Photometer. — The principle on which this photometer is built (Fig. 182) was discovered independently by Blondel in France and Ulbricht in Germany.* The photometer con-

* *Bulletins de la Société Internationale des Electriciens*, 1904, p. 687. *Elektrotechnische Zeitschrift*, 1905, pp. 512 and 1047; 1906, p. 50.

sists of a large opaque sphere painted inside in diffusing white. The lamp L_1 under test is placed somewhere within the sphere (not necessarily in the center); a small opening, covered with a translucent screen p_1 is provided in the sphere. This screen is illuminated by the diffusedly reflected light of the whole sphere, but is protected from the lamp by a small opaque screen q. The illumination of p is proportional to the mean spherical intensity of the lamp L_1, and is balanced against a standard lamp L_2, as in any ordinary photometer. The same formula is used which is given above for the Matthews' photometer. The constant of the instrument is determined experimentally by placing

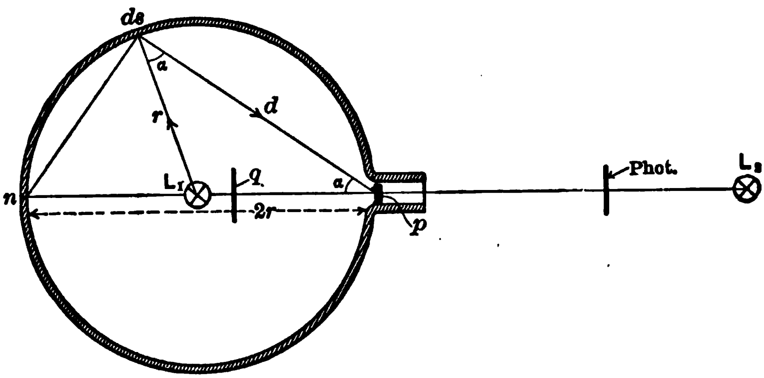

FIG. 182. General arrangement of the Ulbricht integrating photometer.

in the sphere a lamp whose mean spherical candle-power has been determined by integration, as in § 197.

We give here a proof that the illumination of the screen p is proportional to the mean spherical intensity of the lamp L_1. Assume first, for the sake of simplicity, that L_1 is placed in the center of the sphere, and consider the illumination of an element ds of the surface of the sphere. Its normal illumination is proportional to J/r^2, where J is the candle-power of the lamp in the direction under consideration, and r is the radius of the sphere. The element ds illuminates the screen p; according to Lambert's law of diffused light, mentioned above, the quantity of light emitted towards p is $(J \div r^2) . ds . \operatorname{Cos} \alpha$. This light is incident on p at an angle α; hence the normal illumination of p is proportional to

$$\frac{J \operatorname{Cos} \alpha \,.\, ds}{r} \,.\, \frac{\operatorname{Cos} \alpha}{l^2} \text{ or proportional to } \frac{J\, ds}{4\, r^4},$$

because $l = 2\,r\,.\,\text{Cos}\;\alpha$, from the triangle *pn ds*. The total normal illumination of p caused by the whole sphere is thus proportional to

$$\frac{1}{4\,r^4}\int_0^{\pi r^4} J\,ds = \text{Const.} \times \text{mean spherical intensity;}$$

see equation (1) in § 196. This proves that the illumination of the screen p is proportional to the mean spherical intensity of the lamp L_1.

The same is true, when the lamp L_1 is not in the center of the sphere. Let j be the intensity of *normal* illumination of the element ds. The normal illumination produced by this element on the screen p is, as before, proportional to

$$j\,.\,\text{Cos}\,\alpha\,.\,ds\,\frac{\text{Cos}\,\alpha}{l^2} = \frac{j\,ds}{4\,r^4}$$

so that the total illumination of p is proportional to

$$\int j\,.\,ds.$$

This expression is evidently proportional to the total light emitted by the lamp L_1, because this lamp is the only source of illumination of the sphere. The integral does not depend on the position of L_1. The result is not changed by the fact that part of the light is absorbed by the walls, or is reflected several times before it reaches p. This merely changes the constant of the instrument, which must be determined experimentally.

201. Mean Hemispherical Intensity. — In some cases the only useful light of a lamp is that thrown below the horizontal plane passing through its center; this is true, for instance, in street lighting. Lamps used for such purposes should be rated on the basis of their mean *hemispherical* intensity, taking into account only the light emitted below the horizontal plane. Denoting this intensity by J_{mhs} we obtain, in a way similar to that in which formula (2) is deduced,

$$J_{mhs} = \int_0^{\frac{\pi}{2}} J\,\text{Sin}\,\theta\,.\,d\theta;$$

Also the expression

$$J_{mhs} = \frac{\pi}{2\,m}\sum_0^n J\,\sin\,\theta,$$

corresponding to formula (3); m is the number of parts in which 90 degrees is subdivided.

Mean hemispherical intensity may be calculated by using either this last formula or the lower half of the Rousseau diagram (Fig. 180). It can also be measured directly by either of the integrating photometers described above. If the Matthews photometer is used, the mirrors in the upper quadrant are covered or removed. In using the Ulbricht photometer, a horizontal segment of the sphere is removed, or painted black to make it inefficient; the lamp is placed with its center in the horizontal plane separating the upper segment from the rest of the sphere. The illumination of the diffusing part of the sphere is then produced only by the light given out below this plane; therefore, the amount of light received by the screen *p* is proportional to the mean hemispherical intensity of the lamp.

202. EXPERIMENT 9-E. — Determination of Mean Spherical Intensity of Incandescent Lamps with an Integrating Photometer. — Either the Matthews or the Ulbricht photometer may be used (§§ 199 and 200). If possible, take measurements with the same lamps that were tested in experiment 9-D (§ 197). Calibrate the photometer with one of these lamps, and with the constant thus obtained check the mean spherical intensity of the other lamps. If the Matthews photometer is used check the curve of distribution of luminous intensity of one of the lamps by using two mirrors at a time, all other mirrors being covered with black cloth. Devise a method for checking the angular position of the mirrors and for determining their coefficient of absorption. If an Ulbricht photometer is used, investigate the accuracy of the theoretical conclusion that the illumination of the screen is independent of the position of the lamp. For one of the lamps, determine the mean hemispherical intensity, and check it with that calculated from the Rousseau diagram.

NOTE. For further details in regard to practical photometry see Chapter XXXVI, on Interior Illumination, in Volume II.

CHAPTER X.

ARC LAMPS.

203. THE physical phenomenon of an electric arc between two carbons is so commonly known, that it seems hardly necessary to go into a detailed explanation of it.

Carbons are shown schematically in Fig. 183; the sketch to the left represents a direct-current arc; that to the right an alternating-current arc. In the direct-current arc the upper (positive) carbon forms a

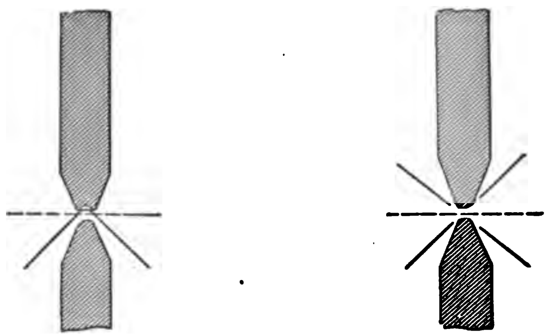

FIG. 183. A direct-current arc, with crater, to the left. An alternating-current arc, without a crater, to the right.

"crater," from which light is thrown down, in the direction where it is mostly needed. With the alternating-current arc no such crater is formed, and the light is distributed fairly equally in all directions, a large amount of it being thereby wasted. Moreover, a direct-current arc gives, with the same watts input, considerably more light than an alternating-current one. This makes the direct-current arc lamp superior to the alternating-current lamp, the more so since the latter makes an unpleasant humming noise, which may often be objectionable, especially in indoor use.

Nevertheless, the advantages of *energy distribution* by means of alternating currents are so great that alternating arcs are coming more and more into use. This is especially true in application to street lighting; while it is an easy matter to produce voltages up to, say, 10,000 volts

by means of alternators and step-up transformers, continuous-current machines for such voltages have serious drawbacks because of commutator troubles, and are gradually going out of use. Thus, it must be understood that while direct-current arcs are themselves preferable, alternating-current arcs afford better current distribution over considerable areas.

204. Types of Arc Lamps.—Arc lamps used at present can be subdivided into direct-current lamps and alternating-current lamps; also into lamps intended for being connected in series, and those to be used in parallel. This gives four commercial types of lamps: series direct-current, multiple direct-current, series alternating-current, and multiple alternating-current. Multiple lamps are used for indoor lighting, and in other cases where lamps are connected to a low-tension network. Series lamps are used for street lighting, where as many as 100 lamps can be connected in series on a special high-tension circuit, with a very small expense of line copper.

Practically all arc lamps in use at present have so-called inclosed arcs, — the carbons are surrounded by a small globe which practically excludes the air. The advantage of such an arrangement is that the rate of consumption of the carbons is much lower. While an open arc lamp requires carbons to be renewed, say, every 10 hours, or even more frequently, inclosed lamps will burn as long as 150 hours or longer. This means a considerable saving in trimming service and carbons. The light of an inclosed arc lamp is much softer and steadier; the fire risk in indoor use is less, because the small globe surrounding the carbons prevents the falling of sparks.

The desire to increase the luminous efficiency of arc lamps led to the development of so-called "flaming" arcs. In these lamps the two carbons are placed vertically side by side at a small angle to each other, and a fan-shaped arc is formed downward; no inclosing (inner) globe is used. The carbons are impregnated with salts which give a soft yellow or reddish color and produce a flaming effect, thereby greatly increasing the efficiency of the lamp. Another new lamp is the "magnetite" lamp invented by Dr. Steinmetz. It is a direct-current arc in which magnetic oxide of iron, or magnetite (Fe_3O_4), is used as negative electrode, copper as positive; the arc is formed by the magnetite vapor. This lamp gives a brilliant white light, and its efficiency compares favorably with that of ordinary inclosed arcs. The flaming arcs and the magnetite lamp present marked advantages, although thus far they have been used to a limited extent only.

205. Regulating Mechanism of Multiple Lamps.—The arc must be adjusted to a definite voltage and current, in order to give a certain

amount of light and to be steady and noiseless. Therefore, arc lamps are always provided with a regulating mechanism, which automatically feeds the carbons as they burn out, and so keeps the distance between them constant. *The mechanism of multiple lamps needs to regulate for constant current only,* because the voltage between the wires is kept constant from the power house. On the other hand, *the mechanism of a series lamp must regulate for constant voltage only,* since the current is kept constant by means of special regulating devices in the power house.

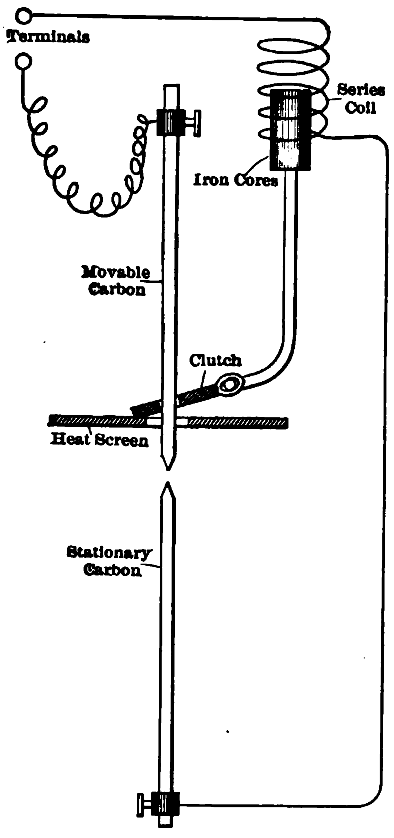

FIG. 184. Mechanism of a multiple arc lamp (series-coil control).

The regulation of *multiple lamps* (sometimes called constant-potential lamps, since they burn on constant-potential circuits) is usually brought about by an electromagnet or solenoid, connected directly in series with the arc (Fig. 184). This solenoid operates a clutch and feeds the upper carbon when required. The current from the lower terminal flows through the upper carbon, the lower carbon, then through the regulating coil and back to the upper terminal. The lower carbon is stationary, the upper is fed down by gravity when it is released by the clutch.

When current is off, the regulating coil does not support the upper carbon, and it rests on the lower carbon, keeping the arc circuit closed. The power being switched on, a current passes through the lamp and energizes the coil; the coil pulls up the upper carbon and starts the arc. The lamp is so regulated, that when the distance between the carbons, and the current through the lamp, are correct, the pull of the coil just balances the weight of the upper carbon with its carriage and other moving parts. When the upper carbon is being burned, the arc becomes longer, its resistance increases, and less current flows through

the coil. The coil can no longer support the upper carbon, and it is lowered until, — due to the decreased resistance (shortened arc), — sufficient current again flows through the coil to support the carbon. This occurring several times, the clutch reaches the lower limit of its travel where it strikes against the stop. The carbon is thereby released and slides down, until the current rises to its normal value. Then the plunger is pulled up again, the clutch grips the carbon and prevents its further motion. In this way the upper carbon is fed gradually in proportion as it is burned, and the coil regulates automatically to maintain constant current.

A resistance is always connected in series with a lamp operated in multiple, the purpose of the resistance being to take up the surplus of the line voltage. An ordinary inclosed lamp does not require more than 75 volts at its terminals, while the usual line voltage is 110 volts; the extra 35 volts must be absorbed in a "ballast" resistance. This resistance also makes the arc steadier and reduces the first inrush of current when the lamp is started.

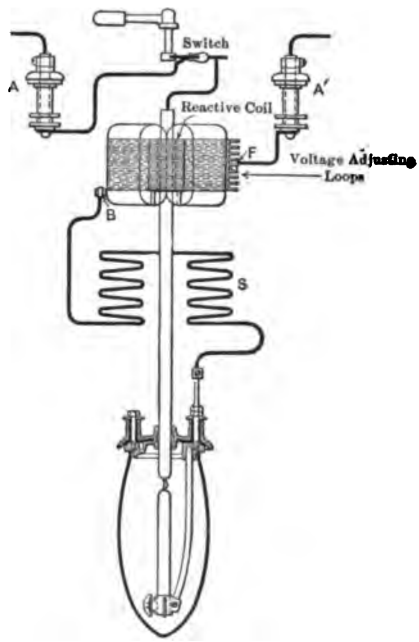

FIG. 185. The Fort Wayne multiple alternating-current arc lamp.

Alternating-current lamps have a similar construction (Fig. 185), except that the plunger — operated by the coil *S*, — must be laminated to prevent eddy currents in it. A reactance coil is sometimes used in place of a ballast resistance. Such a coil is shown on top of Fig. 185; it has several taps *F* in order that the same lamp may be used with different voltages and different frequencies. An advantage of using a reactive or choke coil instead of a resistance is that the coil consumes much less power. The disadvantage of the reactive coil is that it lowers the power factor of the system, and makes the voltage regulation of the alternator unsatisfactory.

206. EXPERIMENT 10-A.—Operation of Multiple Arc Lamps.— Thoroughly inspect the lamp available for study and operation, making

clear to yourself the office of the various parts. Connect it in series with an ample regulating resistance and apply current. Adjust the current and the voltage until the lamp gives a good steady light. While adjusting the lamp, study the arc by throwing its enlarged image — by means of a lens — upon a screen (or a white wall). When observing the arc itself, use dark-colored or smoked glass to protect the eyes.

Try various adjustments of the parts of the lamp: — the counter-weight, the dash-pot, the resistance, etc.; find the limits of volts and amperes between which the lamp gives a satisfactory operation. Determine the exact values of current and voltage at which, in your opinion, the lamp gives the best service. It is well to have a short-circuiting switch around the ammeter to protect it when starting the arc; the lamp takes much more current when the carbons are in contact than in regular operation. Repeat similar tests with a few other arc lamps, using direct and alternating current.

Some time must elapse before the arc becomes steady; therefore, do not take readings too soon after the current has been switched on for the first time. This is especially true for inclosed lamps, because the oxygen within the globe must first be used up and a definite gas mixture and temperature established. To see this more clearly, take off the inner globe and start the lamp in the open air; observe the difference in volts, amperes, and in the quality and general appearance of the light. Before doing this do not fail to introduce more resistance into the circuit; do not keep the current on with an open arc more than a few minutes, since the lamp under such conditions takes an excessive current.

An important point upon which the satisfactory operation of arc lamps depends is *the quality of carbons* used; the best lamp will give a poor and unsteady light with inferior carbons. Make a few simple tests on carbons, as described in Foster's "Pocket Book," pp. 577–578.

Report. Give a short description of the lamps tested; illustrate their construction with rough sketches; describe the tests; give numerical results, and state any peculiarities observed.

207. Regulating Mechanism of Series Arc Lamps. — When several arc lamps are connected in series, as in street lighting, the same current must of necessity flow through all of them. Therefore, the current strength must not be regulated by each lamp independently, but must be kept constant at the distributing point, — the regulating mechanism of each lamp having merely to adjust the distance between the carbons so as to maintain the proper voltage at their terminals. Consider, for instance, the case of ten lamps connected in series, each rated to con-

sume 6.6 amperes at 70 volts. The total pressure at the terminals of the circuit must be 700 volts; this does not, however, necessarily imply that each lamp would take one tenth of it, or 70 volts. The carbons in one of the lamps may stick together, reducing the voltage drop across this lamp almost to zero; while the next lamp may draw such a long arc as to require nearly 140 volts at its terminals. The average voltage still would be 70 volts per lamp. To prevent this, the regulating coils in the lamp itself (Fig. 186) are so adjusted that they automatically maintain the right voltage at the lamp terminals.

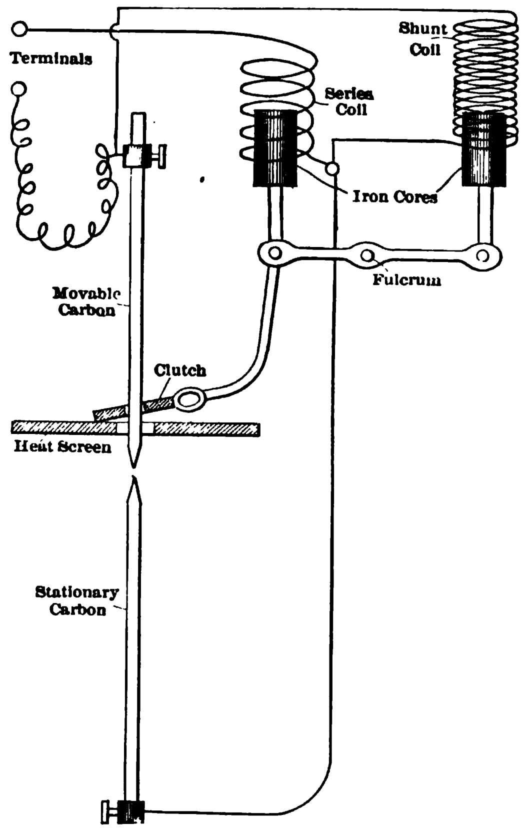

FIG. 186. Mechanism of a differential arc lamp for series connection (series- and shunt-coil control).

Thus, it must be clearly understood, that when lamps are operated in parallel, their regulating mechanism is made to maintain constant current, the voltage being maintained constant from the power house. When the lamps are operated in series, their regulating mechanism must maintain a constant voltage, the current being maintained constant at the power house.

Regulation for constant voltage is obtained by adding a second coil to the mechanism of the lamp shown in Fig. 184. This coil (Fig. 186) is shunted across the arc, and opposes the action of the series coil; for this reason such lamps are sometimes called differential lamps. When the power is off, the upper carbon rests on the lower. When the circuit is closed, the series coil is fully energized and pulls the carbons apart, starting the arc. The carbons being originally close together, the voltage across the arc is low, and therefore the action

of the shunt coil weak. When the carbons are brought up to the right distance, the action of the two coils and of the weight of the moving part just balance each other. When the carbons are sufficiently burned out, the resistance of the arc increases, the voltage across it rises, and the action of the shunt coil becomes stronger than that of the series coil. The shunt coil pulls up its plunger and lowers the carbon. Should the carbons on the contrary come too close together, the action of the series coil becomes stronger than that of the shunt coil, and the former pulls the carbons apart.

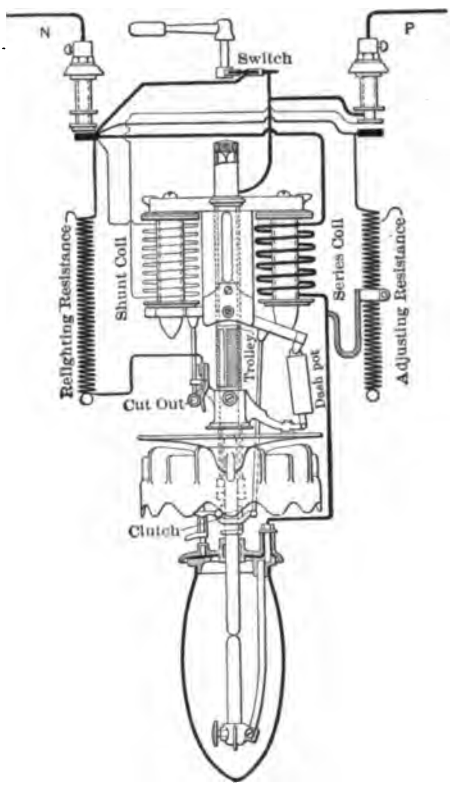

FIG. 187. The Fort Wayne differential arc lamp.

208. Example of a Series Arc Lamp. — A series enclosed arc lamp for direct current is shown in Fig. 187. *P* is the positive terminal, *N* the negative; the main circuit is from the positive binding post to the carbon tube, trolley, upper carbon holder and carbons, through the series coil and the adjusting resistance in parallel with it, to the negative binding post. The shunt circuit is from the positive binding post, through the shunt coil to the negative binding post. When not in operation, the lamp is short-circuited between *N* and *P* by the switch shown on top, the current then passing directly to other lamps in the same circuit.

Opening the switch by turning it puts the lamp mechanism in circuit. The carbons are normally together when the current is off. Turning the current on energizes the series magnet. This attracts the armature carrying the clutch which grips and raises the upper carbon and establishes an arc. The adjusting resistance in parallel with the series coil permits more or less current to pass through the series coil, thus strengthening or weakening its effects on the armature. Counter-

balancing the effect of the series magnet on the armature is the shunt magnet, which is affected by the entire difference of potential existing between the lamp terminals. The action of these two coils is the same as in Fig. 186. The too rapid movement of the armature is prevented by the air dash-pot connected to one end.

If the series magnet draws too long an arc, or the carbon fails to feed, the increased resistance of the arc causes the shunt magnet to become abnormally energized, so that it closes the cut-out contacts and shunts the current around the lamp through the re-lighting coil. This action usually causes the carbons to drop together, after which the series magnet is again automatically cut into circuit and the arc re-established. If, however, the upper holder fails to feed because of the upper carbon being burned out, the shunt magnet holds the cut-out contact permanently closed. The lamp is thus replaced by a dead resistance, and the conditions of burning of the other lamps in the same circuit remain intact.

The adjusting resistance not only permits the adjustment of the lamp voltage, or of the distance between the carbons within certain limits, but also compensates for the influence of temperature. The resistance of the shunt coil becomes considerably higher after the lamp has been in operation for an hour or two, than when the lamp is first started; consequently the current in the shunt coil decreases, and the shunt coil becomes too weak to counterbalance the action of the series coil. But the series coil is shunted by the adjusting resistance made of a material having a low temperature coefficient, — for instance, German silver; therefore, as the series coil becomes heated, more and more current flows through the resistance, instead of through the coil, and the pull of the series coil is also decreased. With a correct design it is possible to maintain the same regulation of the hot lamp as when it is cold.

209. EXPERIMENT 10-B. — Operation of Series Arc Lamps. — The conduct of the experiment is similar to that of Experiment 10-A (§ 206). The performance of a series arc lamp may be studied more satisfactorily on a constant-current circuit than on an ordinary constant-potential circuit. Constant current may be obtained by means of either a suitable generator (§ 211) or an arc-light transformer (§ 213). Both machines are intended for rather high voltages, necessary with several lamps in series; for study it is advisable to have only two or three lamps in series, replacing the rest of the lamps by some ballast resistance. The operation of the lamps is much steadier under such conditions.

210. Means for Maintaining Constant Current. — It is explained in § 207 that when arc lamps are operated in series, current must be

maintained constant from the power house. The first series arc lamps on the market were built for direct current, and special constant-current generators were used to operate them. Of these the Thomson-Houston, the Brush and the Wood arc-light machines have been the most popular. With the advent of the alternating-current arc lamp these machines have been gradually abandoned; regulation of alternating-current circuits being accomplished far more simply by constant-current transformers (Fig. 188).

Dr. Steinmetz, in connection with his magnetite lamp (§ 204), proposed to use *mercury vapor rectifiers* in connection with direct-current arc-lamp circuits. The magnetite lamp is essentially a direct-current lamp; a rectifier is placed between the lamps and the secondary of the constant-current transformer. In this way, the lamps are fed with high-tension pulsating unidirectional currents, while the generation, transmission and regulation are accomplished with all the simplicity inherent to alternating currents. This system apparently has good chances for success, although the mercury rectifier has not yet had a sufficient practical test as to its reliability.

211. Thomson-Houston Arc Light Machine. — Although this type of constant-current machine has been much used in direct-current arc lighting, the machine is no longer manufactured. Many of them are still, however, in regular operation. These machines have been built for voltages up to several thousand volts, and for outputs of from 6 to 10 amperes. The Thomson-Houston machine is a series-wound bipolar generator. The armature consists of three coils connected together on one end; the other ends are connected to three commutator segments; the arrangement resembles the star connection of a three-phase system. In view of the small number of commutator segments, the current generated is a unidirectional pulsating current rather than direct current. The machine is provided with two positive and two negative brushes, so that the circuit is not opened when the brush passes from one commutator segment to the next. The voltage of the machine is regulated by changing the distance between two brushes of the same polarity. This is done automatically by a solenoid mounted on the machine itself, and energized by the main current. The solenoid operates a rocker arm on which two of the brushes are mounted.

This solenoid, or the *regulator*, as it is called, is brought into action by a relay *controller* usually placed on the wall near the machine. The controller keeps the regulator winding short-circuited as long as the current is below normal. Should the current rise above normal, the controller removes the short-circuit on the regulator, and the latter

increases the distance separating the brushes of the machine; this reduces its voltage and consequently the current. With such an arrangement, it is possible to keep the current constant within wide limits of voltages, — in other words, with a varying number of lamps in the circuit.

Some other features of the machine are: (a) the regulator is provided with a dash-pot to prevent jerky action; (b) an air-blast is directed on the brushes to reduce inevitable sparking; (c) the series field winding is shunted by a field rheostat for hand regulation; (d) a non-inductive resistance is connected across the relay contacts to absorb the inductive kick, when the regulator circuit is opened or closed.

212. EXPERIMENT 10-C. — Characteristics of an Arc-Light Machine. — An arc-light machine, such as described in the preceding article, may be conveniently loaded, for a study of its characteristic performance, on a rheostat consisting of, say, 20 resistances in series, each approximately equivalent to an arc lamp. Each resistance is provided with a short-circuiting switch, as in the case of a regular series arc lamp (Fig. 187). Begin the test on open circuit, when both amperes and volts are zero; then close the circuit on a high resistance, and gradually reduce the number of lamps, or equivalent resistances, until the machine is short-circuited. The voltage of the machine is nearly proportional to the number of lamps in the circuit; the current remains constant within a wide range of voltages, down almost to a short-circuit of the machine.

Read volts and amperes; note the number of sections of the rheostat in series. Having finished this run, investigate the limits within which the characteristics of the machine may be changed by (a) shunting the series field; (b) adjusting the brushes; (c) the controller; (d) the regulator, and (e) the dash-pot. Test how quickly the machine regulates with sudden changes in resistance, which are apt to occur in an arc-lamp circuit.

In working with this machine, the student must avoid touching any live parts of the circuit, since the voltages involved may give him an unpleasant shock.

Report: Plot volts and amperes to ohms resistance in the external circuit as abscissæ, or — what is practically the same — to the number of lamps in series. Give the results of various adjustments made on the machine, and its behavior with sudden changes in resistance.

213. Constant-Current Transformer. — Commercial alternators supplying current for light and power are essentially *constant-potential* machines, while *constant current* is required for supplying series arc

lamps. The usual apparatus, which converts constant-voltage energy into constant-current energy, and thus allows arc-light circuits to be fed from ordinary alternators, is called a constant-current transformer; sometimes also tub transformer, or arc-light transformer.

A constant-current transformer (Fig. 188) consists, like any ordinary transformer, of two windings placed on an iron core, thus acting inductively upon each other. The essential feature of the transformer is that its secondary coil is movable, while in ordinary constant-potential transformers both coils are stationary. The stationary primary winding is connected to the alternator circuit; the movable secondary coil

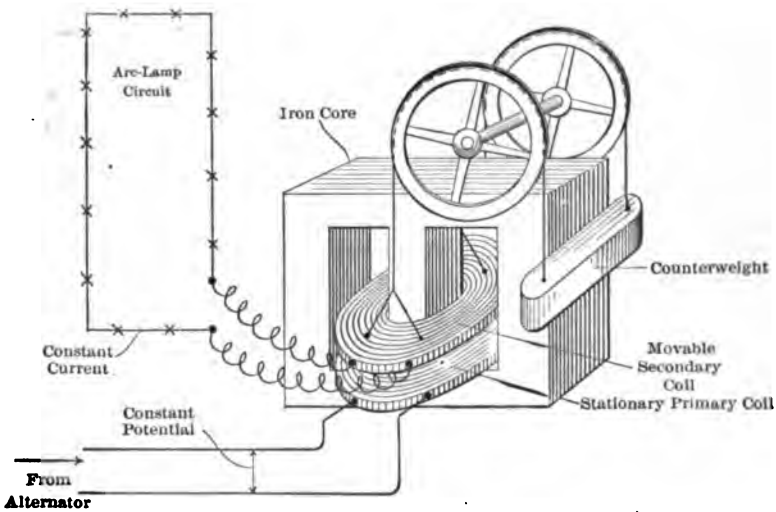

FIG. 188. An arc-light transformer, for transformation of constant-potential energy into constant-current energy.

is connected into the arc-lamp circuit. When the arc-lamp circuit is open, the secondary coil rests on the primary, since only part of its weight is balanced by the counterweight. Closing the arc circuit causes secondary currents to flow in the movable coil, and it is repelled upward. The farther it is repelled, the lower becomes the electromotive force induced in it, this being due to the magnetic leakage between the two coils, which increases as the distance between the coils increases. The counterweight is so adjusted, that with any position of the movable coil, the secondary current in it remains practically constant. When the number of lamps, or the resistance of the circuit, decreases, the current tends to increase; this increases the repulsion between the coils, and the movable coil is repelled farther upward. The use-

ful flux is thereby reduced, consequently the induced current again decreases.

Large arc-light transformers are provided with two stationary and two movable coils, mounted on the same core. One set of coils is independent of the other, and the secondaries are connected to different arc-lamp circuits. Each movable coil is provided with a separate counterweight.

214. EXPERIMENT 10-D. — Operation of a Constant-Current Transformer. — Constant-current transformers are used in connection with series alternating-current arc lighting, and are described in the preceding article. Small transformers of this kind, suitable for only 6 arc lamps in series, are now manufactured. They are very convenient for studying characteristics, without handling voltages above 500 volts. Connections are made as in Fig. 188; the same rheostat, equivalent to arc lamps, may be used, as described in § 212. Have an ammeter, a voltmeter, and a wattmeter in both the primary and the secondary circuits.

(a) Begin the test with the secondary circuit open; then close it on a high resistance, and gradually reduce the resistance by equal steps to zero. Take readings, at each step, on all the instruments, and note the positions of the secondary coil by means of a scale marked on the core.

(b) Determine the limits of current within which the transformer (with suitable counterweight) is capable of regulating for constant current; for instance, with a transformer rated at 6.6 amperes try the regulation at 5 amperes and at 8 amperes.

(c) Note the effect of the secondary load being somewhat inductive, as is the case with actual arc lamps.

(d) Determine how promptly the transformer acts with sudden changes of resistance.

(e) Measure voltages induced in the movable coil in various positions, with the secondary circuit open; also when the secondary circuit is closed on a constant resistance. Do this by moving the counterweight by hand; be careful not to overload the windings by bringing them too close together.

(f) Determine for several values of the load, the phase relation between the primary and the secondary volts; also between the corresponding amperes.

The relation between the voltages can be found as follows: Let the primary terminals of the transformer be denoted by A_1 and B_1; the secondary terminals by A_2 and B_2. Connect B_1 and B_2 together; measure the voltages A_1-B_1, A_2-B_2, and A_1-A_2. The vectors of these

voltages form a triangle from which the phase relation may be determined.

The phase relation between the currents can be determined by using temporarily a common wire for one side of the primary and of the secondary circuits, and connecting an ammeter in this line. Read primary amperes, secondary amperes, and common amperes. This again gives a triangle of vectors, from which the phase relation may be determined. The phase relation between the primary volts and the corresponding current is obtained from the wattmeter reading; so also for the secondary quantities. As a check on the relations thus obtained, connect the wattmeter so as to read primary volts and secondary amperes, and then vice versa.

When working with this transformer, the student should be careful not to touch any live parts of the secondary circuit, as he might receive a shock due to several hundred volts.

Report. Plot to ohms resistance in the secondary circuit as abscissæ (or to its equivalent, the number of lamps in series): primary and secondary volts, amperes, watts, power factor, positions of the secondary coil. Give the results of tests enumerated under (b), (c), (d), and (e). Plot vector diagrams, as required in (f), and explain the relations obtained between the currents and the voltages.

ARC-LAMP PHOTOMETRY.

215. The principles of photometry, or of the art of measuring luminous intensities of lamps, are explained in Chapter IX, and the reader is supposed to be familiar with them. In arc lamps, as in incandescent lamps, the mean horizontal intensity, or the mean intensity measured in any other direction, affords a simple method for rating lamps; but it is not sufficient for a judgment of the total amount of light which a lamp is capable of giving. The trend of opinion among engineers is more and more towards rating arc lamps on the basis of their mean spherical (§ 195) or mean hemispherical (§ 201) candle-power. This is done either by taking a curve of distribution of luminous intensity (Fig. 180) or by means of integrating photometers (§ 219).

The principal points of difference in photometering incandescent lamps and arc lamps are as follows:

(1) Arc lamps are much more powerful sources of light than incandescent standards to which they are compared; therefore, for measurement, the luminous intensity of the arc must usually be reduced in a known ratio.

(2) Since it is not practicable to spin an arc lamp in order to obtain its mean candle-power, the distribution of light is obtained by means of suitable mirrors.

(3) The light of an arc lamp is not quite steady; the arc flickers, runs around the edge of the carbons, the distance between the carbons varies, etc.

(4) Differences in color (§ 193) are more pronounced than with incandescent lamps.

The methods, by which these difficulties are taken care of, are described below.

216. Distribution of Light about an Arc Lamp. — Prof. Matthews'

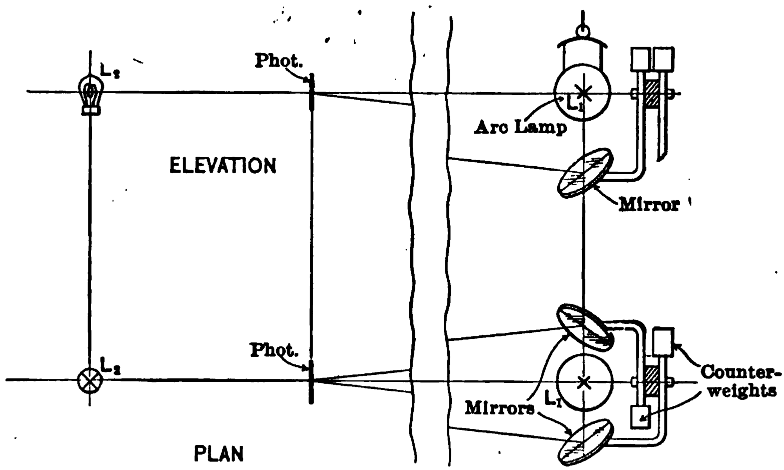

FIG. 189. An arrangement of mirrors for photometering arc lamps.

arrangement is shown in plan and elevation in Fig. 189. It was devised for the extensive tests which he performed upon arc lamps for the National Electric Light Association. The light from the lamp under test is reflected in any desired direction by two movable mirrors and directed upon the photometer screen. The lamp itself is screened from the photometer by a piece of black cardboard, or velvet (not shown in the sketch). With two mirrors, fluctuations in illumination of the photometer screen, caused by an unsteady arc, are considerably reduced, especially those due to the arc running around the edge of the carbon. Either the Bunsen, the Lummer-Brodhun, or a flicker photometer may be used; the illumination on both sides of the photometer screen is balanced by moving the standard lamp L_2. With two mirrors, the illumination of the screen is doubled, so that the result must be

divided by two. It must also be divided by the cosine of the angle at which the rays are incident on the screen, and by the coefficient of absorption of the mirrors. The best way is to find an empirical coefficient for all these effects combined, by placing at L_1 a large incandescent lamp and photometering it with and without the mirrors. Instead of moving the mirrors (to determine the intensity of illumination in various directions) and measuring their angles, it is more convenient to have a complete set of mirrors, as in Fig. 190, and to uncover them two by two.

An arc lamp has to be placed at quite a considerable distance from the photometer screen, in order to be balanced against an incandescent lamp. Where this is not practicable, the light from the arc lamp is reduced in a known ratio. A convenient method is to interpose a revolving sectored disk between the arc lamp and the photometer screen. The disk must be rotated at a speed sufficiently high not to produce flickering; the light is intercepted in proportion to the area of the open and opaque parts (Talbot's law). If the disk consist, for instance, of six sectors, each having an opening of 40 degrees and the opaque part of 20 degrees, two thirds of the light passes through. Suppose the photometer reading to be 400 candle-power; then the true candle-power of the arc is $400 \times 3/2 = 600$ candle-power. The method is not applicable with alternating-current arc lamps, because the light of the lamp itself is fluctuating, and would be intercepted at moments of different intensity. In this case translucent screens are used, or dispersing lenses, to reduce the illumination of the screen; they are calibrated by photometering an incandescent lamp through them and without them.

217. EXPERIMENT 10-E. — Distribution of Light about a Direct-Current Arc Lamp. — The apparatus is arranged as in Fig. 189. Before beginning the experiment proper, determine the constant of the mirrors by measuring the horizontal candle-power of a large incandescent lamp, say 100 candle-power, with the mirrors, and without them. Investigate first the distribution of light around an inclosed arc lamp, as giving the most steady light; use a clear inner globe and no outer globe. Let the lamp burn a sufficient time for the light to become steady; measure the light intensities every five or ten degrees, throughout 180 degrees. Use, if necessary, a rotating sectored disk to reduce the illumination of the photometer screen. Replace the clear globe with a ground-glass one, and again take the distribution curve. Perform the same measurements when the arc lamp is provided with an opalescent outside globe; also with a diffusing reflector, etc. Inves-

tigate the distribution of light around an open arc, a flaming (luminous) arc, a magnetite lamp, etc.

Report. Plot curves of distribution of luminous intensity, as in Fig. 180. Figure out the mean spherical intensity from one of the curves with the aid of the Rousseau diagram (Fig. 180); for another curve by using formula (3) in § 196. Calculate from the same curves the mean hemispherical intensities (§ 201). Give the ratios of the mean spherical and hemispherical candle-power to the mean horizontal candle-power (reduction factors). Discuss the causes of difference in the shape of the photometric curves.

218. EXPERIMENT 10-F. — Distribution of Light about an Alternating-Current Arc Lamp. — For instructions, see the preceding experiment.

219. Arc Lamp Integrating Photometers. — The Ulbricht spherical

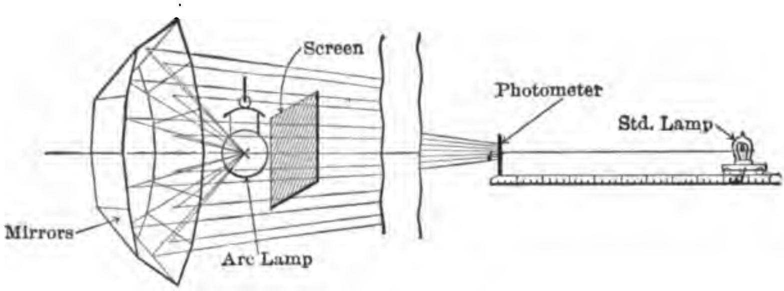

FIG. 190. An integrating photometer for arc lamps.

photometer, described in § 200, may be used for measuring the mean spherical or hemispherical intensity of arc lamps, provided the diameter of the sphere is large enough. Blondel considers a diameter of about 10 feet sufficient for the purpose. Two other practical forms of arc lamp integrating photometers are shown in Figs. 190 and 191.

The photometer shown in Fig. 190 is a development of the photometer represented in Fig. 189. Instead of moving the two mirrors so as to obtain the distribution of light in steps, a set of stationary mirrors is arranged in the form of a truncated pyramid; the light from the lamp is reflected on the photometer screen simultaneously from all the mirrors. The direct illumination of the screen by the lamp is prevented by an opaque shield or screen. Such an arrangement gives an illumination of the photometer screen proportional to $\sum J$, where J is the luminous intensity in a certain direction. However, the mean spherical

intensity, according to equation (3) in § 196, is proportional to $\sum J . \text{Sin}\,\theta$ and not to $\sum J$. Therefore, the light from each pair of mirrors must be reduced, or "weighed," in proportion to its Sin θ, or the area of the zone to which the mirrors correspond (Fig. 180). This is done in practice in three different ways:

(1) Mirrors are smoked to a different degree, so as to reduce their reflecting power in the desired proportion (Matthews).

(2) An opaque screen, with apertures proportional to Sin θ, is interposed between the lamp and the mirrors (Blondel).

(3) Mirrors themselves are spaced so as to correspond to zones of equal areas, being spread farther apart at the poles and crowded near the equator (Russell and Leonard).

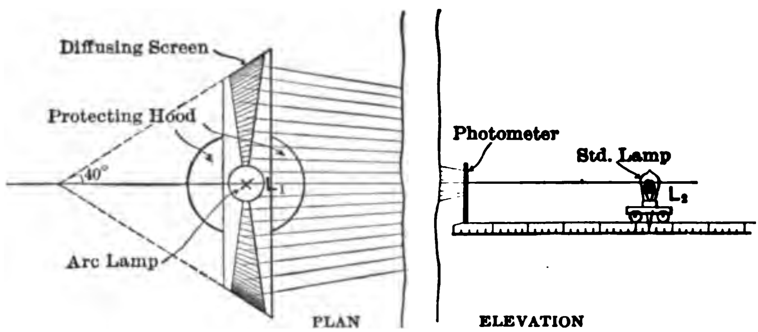

FIG. 191. The Blondel integrating photometer for arc lamps.

Whichever method is used, it is advisable to calibrate the photometer experimentally by a lamp of which the mean spherical candle-power is known.

A modification of the above photometer, devised by Blondel, is shown in Fig. 191. A white diffusing surface is used instead of mirrors: this surface is painted on the inside of a truncated cone. The rays, diffusedly reflected from it, fall on a photometric screen, and the illumination is balanced against a standard lamp. The rays in different directions are "weighed" in the ratio of Sin θ by making the screen the widest in the equatorial plane of the lamp and gradually reducing the width to the poles. The lamp is protected by a hood, so that no light falls on the photometric screen except that reflected from the diffusing surface. The left-hand side of Fig. 191 represents the plan of the device, while the right-hand side is a side elevation.

220. EXPERIMENT 10-G. — Determination of Mean Spherical and Hemispherical Intensities of Arc Lamps with an Integrating Photometer. — A few types of integrating photometers adapted for use with arc lamps are described in § 219. First calibrate the photometer to be used, with a source of light of which the mean spherical intensity is known. Then test in the photometer direct- and alternating-current arcs, both open and enclosed, investigating also the influence of globes and reflectors. Determine the specific power consumption per mean spherical and mean hemispherical candle-power. If possible, the same lamps should be tested as in §§ 217 and 218, in order to check the results.

NOTE. For further details in regard to practical photometry see Chapter XXXVI, on Interior Illumination, in Volume II.

CHAPTER XI.

DIRECT-CURRENT GENERATOR — OPERATING FEATURES.

221. THE essential parts of a direct-current generator are shown in Fig. 192. The machine consists of a revolving part, or armature, in which e.m.f.'s are induced (generated), and of a stationary magnetic field, necessary for inducing these e.m.f.'s. In the particular case shown, the field has four poles.

The armature is driven by a prime mover whose power is thereby transformed into electrical energy and delivered to the line through the

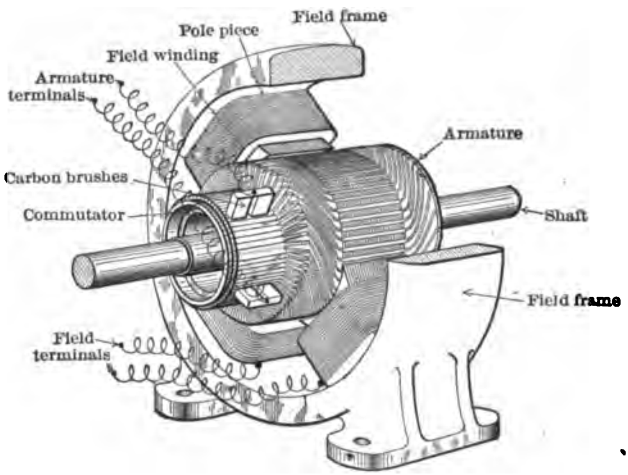

FIG. 192. The principal parts of a direct-current generator or motor.

armature terminals. The armature itself consists of a cylindrical iron core, mounted on the shaft and provided with slots on its periphery. A winding consisting of copper bars or coils is placed in these slots. The coils are properly interconnected so as to assist each other in their electrical action, and are also connected to the so-called commutator shown to the left. The commutator converts alternating voltages induced in the armature into a direct voltage at the terminals of the machine. The commutator consists of copper segments mounted on a

sleeve and insulated from each other by sheets of mica. Two or more sets of stationary carbon brushes make contact with the commutator segments and conduct direct current to the line.

The stationary frame and the poles are made of some magnetic material, such as cast iron or steel. The pole-pieces may be cast with the frame, or cast into the frame, or bolted to it. The poles are provided with windings, through which is sent direct current necessary for exciting the magnetic field. The exciting current is usually generated by the machine itself, as is explained in the next article.

222. Self-Excitation. — The most commonly employed connections between the field winding and the armature are shown in Fig. 193. The field winding consists of many turns of a comparatively small

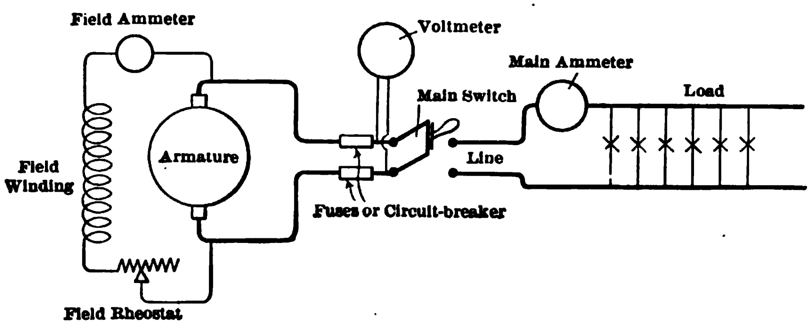

FIG. 193. Diagram of connections between a shunt-wound generator and the load.

wire, and is connected across the brushes of the machine, in other words, in parallel with the armature winding and with the current-consuming devices in the external circuit. Such generators are called *shunt-wound machines*, the field winding being "shunted" across the armature terminals. The rheostat shown in the exciting circuit is for regulating the field current, so as to maintain the proper voltage.

Self-excitation is made possible by virtue of *residual* magnetism in the frame and in the pole-pieces of the machine. The machine once magnetized from an external source retains a small part of the magnetism permanently. When started, with the line circuit open, the residual magnetism induces a small current in the armature; this current flows through the field winding and strengthens the original field. This increased field induces stronger currents in the armature, which sends

a stronger current through the field, etc., until the excitation reaches its full value.

The voltage induced in the armature is proportional to the magnetic flux issuing from the poles (this is according to the fundamental law of induction). The flux itself depends on the value of the exciting current, so that finally the voltage of the machine depends on the exciting or field current (Fig. 194). If iron had a constant permeability, this curve would be a straight line, the magnetic flux and the induced voltage being proportional to the exciting current. In reality the per-

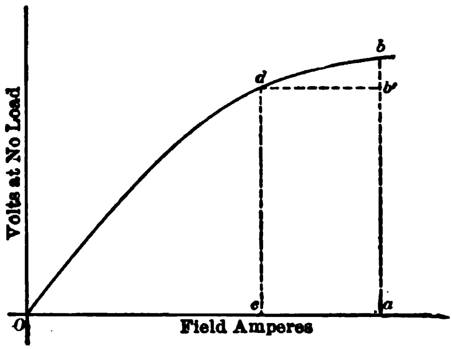

FIG. 194. No-load characteristics.

meability of iron decreases as the flux density increases, the iron being gradually "saturated" (§ 121). This explains the shape of the curve in Fig. 194: the flux, and therefore the induced voltage, increase more slowly than the exciting current. The curve is called the no-load saturation curve, no-load characteristic, or magnetization curve of the machine.

223. EXPERIMENT 11-A.—No-Load Characteristics of a Shunt-Wound Generator.—The purpose of the experiment is to determine the relation between the exciting current and the terminal voltage of a shunt-wound machine at no load (Fig. 194). The generator (Fig. 193) is driven at its rated speed by a belted or direct-connected motor. An ammeter is inserted into the field circuit, and a voltmeter across the brushes; the main line circuit is kept open.

(1) The readings are begun with the highest possible value of the field current, in other words, with the field rheostat short-circuited;

the field is then reduced in steps to zero. Readings should be taken of amperes, volts and the speed of the machine. The value of the residual magnetism at the beginning of the experiment is rather indefinite; therefore it is advisable to begin the excitation at its maximum and reduce it to zero. After this, take readings with an increasing field current, in order to see the influence of residual magnetism. This is analogous to taking a hysteresis loop, shown in Fig. 138.

(2) Induced voltage is proportional to the speed of the machine, provided the field current is kept constant; this is according to the fundamental law of induction. To prove this experimentally, select a field excitation and drive the machine within as wide a range of speed as the driving motor will permit. Keep the exciting current constant by regulating the field rheostat, or excite the machine from a separate source. Repeat this run with two or three different values of field current.

(3) Finally investigate the ability of the machine to excite itself. Run it at the rated speed, and find the rheostat notch on which the field just begins to build up. Measure the corresponding field current, the final voltage, and the number of seconds of time from the closing of the field switch to the moment when the voltage reaches its final value. Repeat the same experiment with less resistance in the field rheostat.

Report. Draw a diagram of the connections used and give a short description of the machine. Plot the saturation curve, shown in Fig. 194, correcting the voltages (by direct proportion) where the speed was above or below normal. Plot curves showng proportionality of voltage to speed. Give numerical results of the experiment on self-excitation.

224. Voltage Drop and Regulation.— One of the most important requirements in practical operation of generators, supplying current for light and power, is that the terminal voltage must be nearly constant, independent of the load. This practically means, that each customer should get the same quantity of light from his lamps, and same speed from his motors, whether many or only a few other customers are using current at the same time.

This condition cannot be strictly fulfilled with a shunt-wound machine, unless the field current is regulated by the field rheostat. Without regulation the voltage drops considerably, as the load increases. This is due to the following three causes:

(*a*) Part of the induced voltage is consumed in the resistance of the armature; this drop (*ir*) is proportional to the armature current, or (practically) to the load of the machine.

(*b*) The armature currents tend to produce a magnetization opposite to that due to the shunt field winding, and in this way weaken the original field (§ 127). The voltage induced in the armature is therefore correspondingly lower.

(*c*) As the terminal voltage of the machine decreases, on account of the above two causes, the current in the shunt winding also decreases in the same proportion. This again weakens the field and reduces the voltage still further.

Curves which show the influence of the load on the voltage of a machine are generally called its characteristics (Fig. 195). They show

$i = \frac{e}{r}$

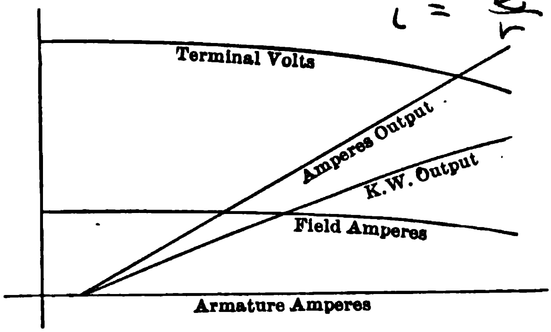

FIG. 195. Performance curves of a shunt-wound generator.

voltage fluctuations of the machine, variation of field current, etc., with changes of load.

When a shunt-wound generator is running on a variable load, the operator usually regulates the voltage from time to time, by means of the field rheostat, keeping it fairly constant. In order to see what regulation can be expected under such conditions, two characteristics may be taken in the laboratory, as corresponding to two extreme cases:

(1) The machine is left *entirely without attention*, so that the voltage fluctuates freely with the load; see § 226.

(2) The switchboard attendant *regulates the field continuously*, thus keeping the voltage absolutely constant; see § 227.

In actual practice an intermediate condition exists: the attendant does not watch the voltmeter constantly, but corrects the voltage from time to time.

According to the standardization rules of the American Institute of Electrical Engineers, the regulation of self-exciting machines is defined as per cent increase in voltage, when full load is thrown off

the machine, the speed and the setting of the field rheostat remaining unchanged. To illustrate, suppose the rated voltage of a shunt-wound generator to be 100 volts. Full load is put on the machine, the field rheostat being adjusted so that the terminal voltage is 100 volts, then the main switch is opened. Let the terminal voltage when the prime mover comes back to the normal speed be 109 volts. According to the above definition, the regulation of the machine is 9 per cent.

225. Components of Voltage Drop. — The curve of terminal volts, shown in Fig. 195, refers to the case when the generator is left without attention, so that all three causes of the voltage drop in the armature (§ 224) take place to their full extent. These three factors are shown separately in Fig. 196.

The ohmic drop *a* is calculated by multiplying the armature current by the resistance of the armature (including that of the brushes). The drop, due to the decrease in the field current, can be found from the no-load characteristic shown in Fig. 194. Knowing from Fig. 195 the values of the field current at no load and at the load under consideration, the corresponding decrease in voltage *bb′* (Fig. 194) can be read off directly on the curve. The remainder of the total observed drop is caused by the armature reaction. In most text-books it is stated that voltage drop in shunt-wound generators is caused by *two* factors: ohmic drop in the armature, and the armature reaction. This is true, so long as the machine is separately excited, or the exciting current is kept constant. In the actual operation, however, the exciting current itself varies with the terminal voltage of the machine, so that in analyzing the voltage drop of a machine *left to itself* (without regulation), this third cause must also be considered.

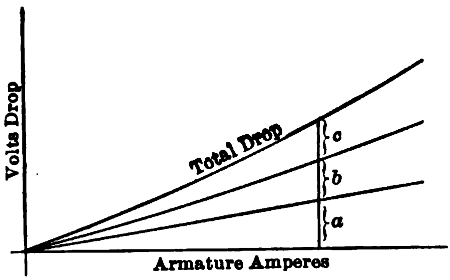

FIG. 196. The components of voltage drop in a shunt-wound generator.

When making a special study of the armature reaction, the field current can be kept constant from no load to full load, by means of the field rheostat. In this case, the voltage drop is caused by *two* factors only: ohmic drop and armature reaction. Subtracting the former, we readily find the magnitude of the armature reaction, with a given load and excitation.

226. EXPERIMENT 11-B. — Voltage Characteristics of a Shunt-Wound Generator. — The purpose of the experiment is to obtain the performance curves shown in Fig. 195 and to separate the voltage drop into its components, as per Fig. 196. This corresponds to the first extreme condition of operation mentioned in § 224. The machine is connected up as in Fig. 193, and is driven at its rated speed by a motor. The readings may be conveniently recorded on a data sheet similar to that shown below.

	Normal Voltage at —— Load.			
	Field Amps.	Load Amps.	Volts.	Speed.
Inst. No.				
Const.				

Bring the machine up to its full speed, and load it on resistances; regulating these resistances and the field rheostat, so as to get the rated voltage of the machine at a load exceeding the rated capacity of the machine by about 25 per cent. Read amperes load, voltage of the machine, and field current; the speed should be kept as nearly constant as possible, throughout the whole test. Now reduce the load somewhat, leaving the field rheostat in the same position as before; in other words, allowing the voltage of the machine to vary at will. Read again, — volts, amperes and field current; then again reduce the load, etc., until all of the load is gradually taken off the machine.

The same test is then repeated with another setting of the field rheostat, — for instance, such that the full rated voltage takes place at 100 per cent, or at 75 per cent of full load; it is also desirable to have a third curve corresponding to such a position of the field rheostat, that the machine gives its full rated voltage at a small load, say about 25 per cent of full load or even at no load. In each case, after having properly set the rheostat, begin the run with about 25 per cent overload, and gradually reduce the load to zero.

Having finished the test, measure the ohmic resistance of the armature, with and without the resistance of the brushes; use the drop-of-

potential method (§ 10). The no-load saturation curve (Fig. 194) is supposed to be known from experiment 11-A; otherwise it should be taken before leaving the laboratory.

Report. Plot the curves, shown in Fig. 195, for the three runs made. Armature amperes are obtained by adding field amperes to load amperes. Kilowatt output is calculated as a product of load amperes by terminal volts, divided by 1000. Figure per cent regulation of the machine at full load, as explained at the end of § 224. For one of the curves separate the voltage drop into its three components, as in Fig. 196.

227. EXPERIMENT 11-C. — Excitation Characteristics of a Shunt-Wound Generator.—This experiment corresponds to the second extreme condition mentioned in § 224, namely, the operator regulates the field rheostat continually so as to keep the terminal voltage constant. The purpose of the experiment is to ascertain the necessary variations in field current. The connections are the same as in Fig. 193; the same data sheet may be used as in the preceding experiment, except that the voltage, instead of the setting of the field rheostat, is now kept constant. Bring up the load and the field current of the machine so as to have the full rated voltage at a reasonable overload, say 25 per cent; then gradually reduce the load and take readings. The resistance in the field circuit must be gradually increased, so as to keep the terminal voltage constant.

Per cent variation in field current depends on the degree of saturation of the machine (§ 121) and is less with highly saturated machines. This is evident when we consider that a larger number of field ampere-turns are required with higher saturation; therefore the same number of armature demagnetizing ampere-turns constitutes a smaller per cent of the active ampere-turns, and its influence is less noticeable.

To see the influence of saturation, repeat the same test at as high a terminal voltage as it is possible to obtain at full load; then perform a similar run at a voltage considerably below normal.

Report. Plot performance curves, as in Fig. 195. Determine per cent variation in field current between no load and full load. Show that the regulation is better the higher the saturation of the magnetic circuit of the machine.

228. Compound Winding. — The above two experiments show that the terminal voltage of a shunt-wound machine decreases as the load increases. In order to keep the voltage constant, it is necessary to regulate the field rheostat, increasing the exciting current as the load increases. The same effect can be obtained automatically by placing

on the pole-pieces a second winding, in series with the main circuit (Fig. 197). As the main current increases, more current flows through the series winding, adding excitation to that supplied by the shunt winding. By properly adjusting the number of turns in the series

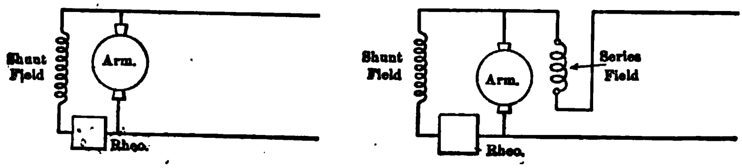

FIG. 197. Shunt-wound generator to the left, compound-wound generator to the right.

winding, the voltage at the terminals of the machine is made practically independent of the load. This additional series winding is called the *compounding winding*, and the machine is called *compound-wound.*

In reality the voltage curve (flat compounded) has an aspect as shown in Fig. 198. The machine compounded so as to give the same

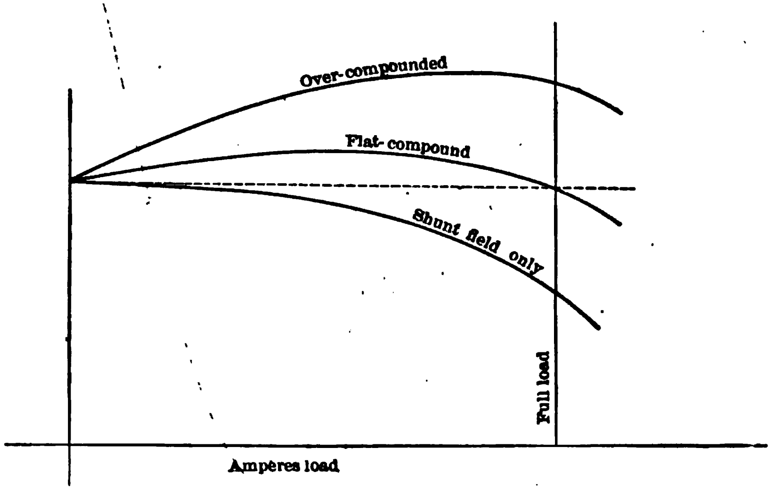

FIG. 198. Effect of series-field winding on voltage characteristics of a generator.

voltage at full load as at no load, gives somewhat higher voltages at partial loads. This is caused by the magnetic flux of the machine being not proportional to the number of exciting ampere-turns. Commercial machines are often designed with such a degree of saturation in the magnetic circuit that this circumstance is scarcely noticeable. In many cases this rise in voltage above normal at partial loads is of

no consequence; if, however, an exact compounding is required, a little regulation of the field rheostat by hand becomes necessary.

By providing more turns in the series winding than is necessary to compensate for the voltage drop, the machine is *over-compounded*, — in other words, its voltage rises with the load (upper curve in Fig. 198). This is frequently done in generators supplying power for electric railways; over-compounding is there necessary to compensate for voltage drop in long feeders, and thus to give a more constant pressure on the trolley wire. Suppose, for instance, that the drop in a feeder at full load is 50 volts; then, in order to give the standard voltage of 500 volts on the trolley wire, the generator voltage has to be 550 volts. At half load the drop in the feeder is only 25 volts; so the generator voltage must be 525 volts in order to give the same pressure on the trolley wire. Finally, at very light loads the drop in the feeder is negligible, and the generator pressure must be about 500 volts. Thus, the curve of the generator pressure must be a straight line, ascending with the current.

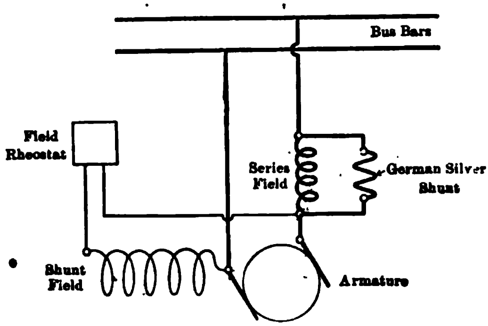

FIG. 199. Diagram of connections in a compound-wound generator, with the shunt-field winding connected across the armature (short shunt).

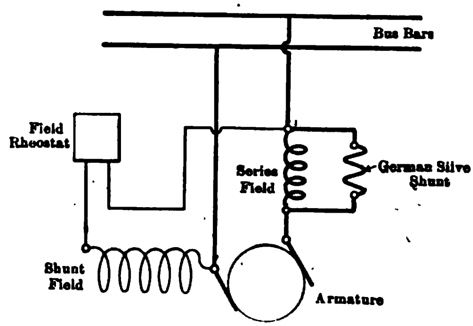

FIG. 200. Diagram of connections in a compound-wound generator, with the shunt-field winding connected across the terminals of the machine (long shunt).

It is difficult to design a machine with the right number of series turns for a certain degree of compounding. The permeability of iron may be somewhat different from that admitted in the calculations, and the armature reaction cannot be predetermined with a sufficient accuracy. Moreover, different customers may desire the same type of machine with a different degree of over-compounding. Therefore, generators are usually provided with a number of series turns, sufficient for a

reasonably high degree of over-compounding, and the *compound winding is shunted* to a desired degree by German silver strips (Figs. 199 and 200), so that only part of the total current flows through the series field. In this way the magnetizing action is reduced, and by varying the resistance of the shunt any degree of compounding is obtained without changing anything in the machine itself.

The shunt winding of compound-wound generators can be connected either across the armature (short shunt, Fig. 199) or across the terminals of the machine (long shunt, Fig. 200). There is not much difference in the performance of these two types, both of which are used in practice.

229. Number of Turns in the Series Winding.— The number of turns in series windings, necessary for flat-compounding, may be determined either by successive trials, or better, by the following experiment: Suppose the machine under test to be a 110-volt 200-ampere generator; let the machine give 110 volts at no load at a field current of 5.5 amperes. When full load is put on and the series winding is disconnected the voltage naturally drops; and in order to raise it to 110 volts the shunt field excitation must be increased to, say, 6.1 amperes. Let the total number of turns on the shunt winding be 2400; then the difference $(6.1 - 5.5) \times 2400 = 1440$ ampere-turns, represents the additional excitation, necessary for compensating the armature reaction and the ohmic drop in the armature. This number of ampere-turns is to be supplied by the series winding at the full-load current of 200 amperes; consequently, in the series winding there must be about 8 turns $(200 \times 8 = 1600$ ampere-turns). This is somewhat more than necessary, but an allowance has to be made to compensate for the ohmic drop in the compounding winding itself.

The number of turns required for any degree of over-compounding may be determined in a similar way. With the same data as before, suppose the machine to give the right voltage (110 volts) at full load, with 8 turns of compounding winding and with the same field current of 5.5 amperes as at no load. Let it be required now to put on more turns of compounding winding, in order to get 116 volts at full load. To determine this additional number of turns experimentally, strengthen the shunt field until the voltmeter reads 116 volts at the terminals of the machine. Suppose the necessary field current to be 6.2 amperes, which corresponds to an additional excitation of $(6.2 - 5.5) \times 2400 = 1680$ ampere-turns. Not all of this excitation, however, needs to be supplied by the series winding, because with the higher terminal voltage the shunt current increases automatically; in our case it will be $\frac{116}{110} \times 5.5 = 5.8$ amperes, which consequently means an increase of

$(5.8 - 5.5) \times 2400 = 720$ ampere-turns; the rest, $1680 - 720 = 960$ ampere-turns must be supplied by the series winding. With a current of 200 amperes, 5 turns will be sufficient to bring about the desired over-compounding (in addition to 8 turns put on before).

If the number of turns in the shunt winding is not known from the design data of the machine, it can be easily determined by exciting the machine separately by a known number of ampere-turns and comparing the voltage thus obtained with that given by self-excitation. For instance, if it takes 72 turns of an auxiliary winding at a current of 100 amperes to excite the machine up to, say, 50 volts, while it takes only 3 amperes to induce the same voltage by using the shunt winding, then the number of turns of the shunt winding is evidently

$$\frac{100 \times 72}{3} = 2400 \text{ turns.}$$

230. EXPERIMENT 11-D.— Exercises in Compounding Direct-Current Generators. — The purpose of the experiment is to investigate the action of the compounding winding explained in §§ 228 and 229. The machine used for this exercise should be a shunt-wound generator; the student himself is expected to provide it with a compound winding. The experiment can be conveniently conducted as follows:

(1) Take a load characteristic of the machine, using it as a shunt generator, that is to say, without the compounding winding. Set the field rheostat so as to get the rated voltage at no load, and then keep it in this position, gradually increasing the load to, say, 25 per cent overload. Note the voltage drop with the increasing load. This run is intended to give an idea of what the regulation of the machine would be without the series winding.

(2) Set the field rheostat and the load resistances so as to get full rated load current at normal voltage. Note the necessary increase in field current.

(3) Determine the number of turns in the shunt winding. To do this, first take a magnetization curve of the machine, using the shunt winding only. Then put a *known* number of turns on the field magnets of the machine, and take the same no-load characteristic, having the machine separately excited through this field. The shunt winding must in this case be kept open. The comparison of the exciting currents in both cases will permit the determination of the number of turns in the shunt winding, as explained above.

(4) From the results of (2) and (3) figure out the necessary number of series turns for flat compounding and place them on the machine.

(5) Check the number of series turns by taking a load characteristic of the machine.

(6) Determine the number of series turns for over-compounding the machine by about 10 per cent, and check the results experimentally.

(7) Shunt the series winding by a German-silver strip, and adjust it so as to again make the machine flat-compounded.

Report. (1) Plot the load characteristics (Fig. 195) with and without compounding winding; also for over-compounding, if sufficient data were taken in the laboratory.

(2) Plot no-load characteristics obtained by using the shunt winding alone, and the series turns alone; explain how the number of turns in the shunt winding was determined from these two curves, and give the numerical results.

(3) Explain how the number of turns of the series winding was predetermined for flat-compounding and for over-compounding.

(4) Give the result of applying German-silver shunts.

231. Tirrill Regulator. — The compounding winding does not give a perfect voltage regulation, nor does it correct for speed fluctuations of the prime mover; moreover, the machine must be made somewhat larger and heavier, in order to accommodate the series winding. Various attempts have been made to do away with the series winding and to regulate the voltage of the machine automatically, — for instance, by solenoids, acting on the shunt-field rheostat. An objection to such regulators is that they are rather sluggish, not following variations in voltage quickly enough.

Mr. Tirrill conceived the idea of accomplishing an automatic voltage regulation by periodically short-circuiting the field rheostat, or a portion of it (Fig. 201). This is done by light vibrating contacts with practically no inertia. The relative lengths of time, during which the rheostat is short-circuited or active, determine the average value of the field current and consequently the voltage of the machine. The leads from the field rheostat are short-circuited between the platinum tips marked "relay contacts"; a condenser is placed across the contacts for reducing sparking. The closing and opening of these contacts is done by the differentially wound electromagnet, controlled by the "main contacts." The main contacts are closed and opened by the control electromagnet connected across the main bus-bars.

The action of the regulator is as follows: Suppose the main contacts to be open; then the left-hand side only of the differential electromagnet is energized; it opens the relay contacts and cuts the field rheostat into the circuit. The terminal voltage of the machine immediately drops below normal. This reduces the current in the control

electromagnet, and the spring above it closes the main contacts. Now a current flows through the right branch of the differential electromagnet and destroys its previous magnetization. The spring above closes the relay contacts and short-circuits the field rheostat. The line voltage rises above normal, the main contacts are again opened, and the operations of the two electromagnets are repeated in the same order. In reality, both contacts are continually vibrating; the periods during which the relay contacts are closed adjust themselves automatically, so as to maintain a constant voltage at the terminals of the machine.

An effect, similar to over-compounding, is produced by providing

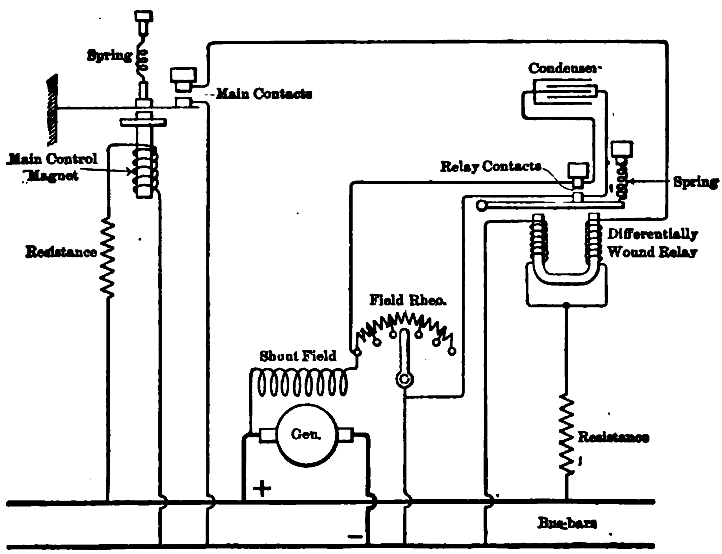

FIG. 201. Diagram of connections of a Tirrill voltage regulator for use with direct-current generators.

an additional series winding on the main control electromagnet. The voltage then rises as the load increases. It is not necessary to send the whole main current through this winding, but merely a small part of it. To accomplish this, a low-resistance shunt is inserted into the main circuit; the series winding of the electromagnet is connected across the terminals of this shunt, as in direct-current ammeters (Fig. 35). The series winding opposes the action of the shunt winding; therefore, with a heavy load on the line the control electromagnet becomes weaker, and the opposing spring keeps the main contacts closed for a comparatively longer time.

Fig. 202 shows the external view of a Tirrill regulator; the main relay contacts are seen to the left, the differential electromagnet to the right. The radial switch below is for connecting the regulator to the field of any of the machines working in parallel. The double-throw switches are for reversing the polarity of the spark, so as to wear the contacts equally.

232. EXPERIMENT 11-E. — Study of Tirrill Regulator. — The regulator described in the preceding article is connected as shown in Fig. 201. The experiment consists in observing its performance under various conditions met with in practice. Vary the load of the machine alternately gradually and suddenly; vary the speed of the driving motor, setting of the field rheostat, adjustment of the regulator springs, etc., noting how the voltage regulation is affected by these changes. Connect the compounding winding of the regulator and observe its action. If two or more generators are available, run them in parallel and have one of them connected to the Tirrill regulator. See if the machines distribute the fluctuating load properly under these conditions; perform this experiment with shunt-wound and with compound-wound machines. Investigate all the factors separately and report the observed results.

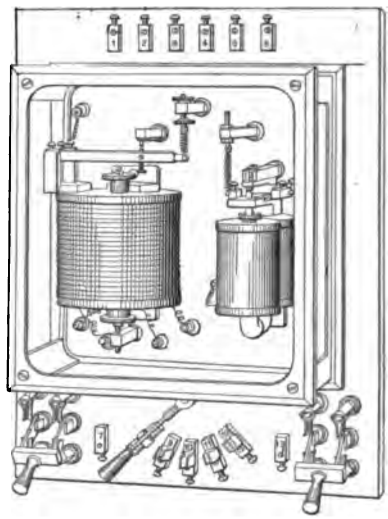

FIG. 202. Tirrill voltage regulator for direct-current generators.

OPERATION IN PARALLEL.

233. It is common practice in power houses to have more than one generator connected to the same bus-bars and operated simultaneously. This gives a more flexible arrangement than one large machine of a size sufficient to supply the heaviest load of the day. The chief advantages of having more than one machine are:

(1) The number of machines actually used during certain hours can be made to correspond closely to the demand; this permits the operation of the machines near the point of their maximum efficiency.

(2) An accident to one machine does not shut down the whole station.

In large power houses it is necessary to use several machines, simply because the total output is considerably above the capacity of the largest generator built.

With the system of distribution of electrical energy used at present (constant-potential system), machines which operate simultaneously are connected *in parallel,* so that each runs at full voltage and supplies a part of the current demand.*

Certain conditions must be fulfilled in order that two or more machines could supply power to the same bus-bars, without interfering with each other, and each take a proportionate share of the total load. When but one machine is connected to the line, the power generated can flow only into the line; when, however, two generators are connected to the same line, the current from the first machine, instead of flowing to the line, may, under certain circumstances, also flow into the second machine, driving it as motor. In this case, the second machine not only does not help the first one, but constitutes an additional useless load for it. Even if this is prevented, and both machines are working as generators sending power into the line, it does not necessarily follow that each machine takes its proper share of load, unless certain conditions are fulfilled.

These conditions are discussed in the following articles; shunt-wound machines are more easily operated in parallel than compound-wound machines, and are therefore considered first.

234. Shunt-Wound Generators in Parallel.—Two identical shunt-wound machines driven by identical prime movers usually run satisfactorily in parallel, and automatically divide the load in two equal parts, for there is no reason why one machine should carry more load than the other. If it should endeavor to take more load, its voltage would drop, and the other machine, becoming electrically stronger, would automatically take up more load.

Referring to Fig. 203, suppose that machine No. 1 is supplying the load and that it becomes necessary to put the other machine in operation. Generator No. 2 is first excited so as to give the same voltage as No. 1 (and the right polarity, of course); then its main switch is closed. The first machine still continues to supply the total load, unless the excitation of the second machine be somewhat *increased* and that of the first machine *reduced.* By regulating the field rheostats of both machines,

* With distribution at a constant current, — for example, for arc lighting (§ 210), or as is proposed for certain long-distance transmission lines, — the machines, if more than one are used, must be connected *in series,* each supplying the total line current, and taking part of the total voltage. The considerations of the present article do not apply to such systems.

the load can be divided in any desired proportion; if the machines are identical in operation each takes its share of load, even with fluctuating current and voltage. One voltmeter only is used with any number of machines in parallel. Each machine is provided with receptacles, such as p_1 and p_2; a plug is inserted in one of the receptacles, and thus connects the voltmeter to the desired machine.

If it is desired to disconnect machine No. 1 and to transfer the whole load to the other machine, this should *not* be done by simply opening the main switch of the first machine. This would cause an arc at the

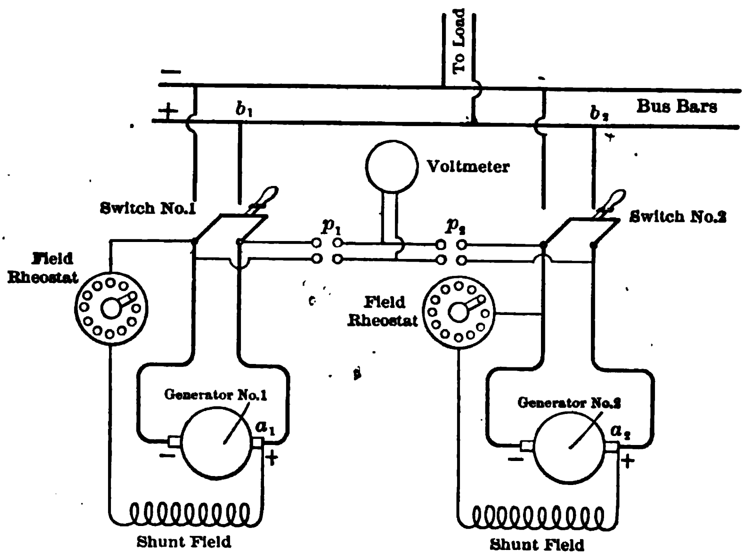

FIG. 203. Two shunt-wound generators in parallel.

switch, the line voltage would drop, and the second machine would experience a harmful shock, as the extra load is suddenly thrown upon it. This may not be noticeable on small laboratory generators, but is of consequence with large machines. Therefore, before opening the main switch of one of the machines its field excitation must be *lowered* and that of the other machine *increased*, until this latter carries practically the whole load. Then the main switch can be opened without disturbing the established electrical relations.

By lowering the field excitation of the first generator still more, its armature current is reversed, and the machine begins to run as *a shunt motor*, driving its prime mover. This, of course, must be avoided in practice, but should it accidentally occur, no particular harm would

be done, as the machine continues to run in the same direction. Some power houses are provided with "reverse-current relays," or special circuit-breakers, which open the circuit of the machine in case the current becomes reversed.

If the two machines have different characteristics, that is to say, voltage drop in one differs from that in the other with increasing load, it may easily occur, that, while the machines divide the current properly at a certain load, the machine which has the smaller internal drop becomes relatively overloaded on heavier loads, and vice versa. Under such circumstances it becomes necessary to artificially "spoil" the characteristics of the better machine, by connecting some resistance in its armature circuit, until it gives the same per cent drop as the other machine. Then the machines will work satisfactorily under all load conditions, unless the degree of saturation in their magnetic circuits is very different.

235. EXPERIMENT 11-F. —Operating Shunt-Wound Generators in Parallel. —The student is given in the laboratory two shunt-wound generators of different type, possessing different characteristics; the machines are connected in parallel, as shown in Fig. 203, and loaded on a rheostat. Take a moderate load and practice in transferring it from one machine to the other, by regulating the field rheostats. Also start and stop one of the machines when the other is running, without disturbing the load. Weaken the field of one of the machines until the current in it is reversed and it is driven by the other machine as a motor. Try to run one or both machines in parallel with the laboratory direct-current supply.

After this, investigate whether the machines divide the current properly at all loads. Take a load nearly equal to the total capacity of the two machines, and adjust the field rheostat so that each machine takes its share of the load. Gradually reduce the load and observe whether it is all the time divided in about the same proportion. If not, introduce some resistance into the armature circuit of the machine that has the tendency to take a larger amount of the load. Adjust the resistance to the best value, and then take a complete curve from full load to no load, showing the current distribution between the two machines.

236. Compound-Wound Generators in Parallel.—Two compound-wound generators, connected to the same bus-bars, are shown in Fig. 204. The general scheme of connections is the same as in Fig. 203, except for the addition of the series windings of the machines. The series windings are provided, if necessary, with German-silver shunts

(Figs. 199 and 200). It may seem at first that the addition of series windings should not in any way affect a satisfactory operation of the machines, and that all that has been said in regard to shunt-wound machines, is directly applicable to compound-wound generators.

Experience shows, however, that two compound-wound generators do not run stable enough in parallel, unless an *equalizing* connection E_1E_2 is established between the brushes a_1 and a_2, adjacent to the series windings.

The cause for this is as follows: Suppose first, that the switch E_1

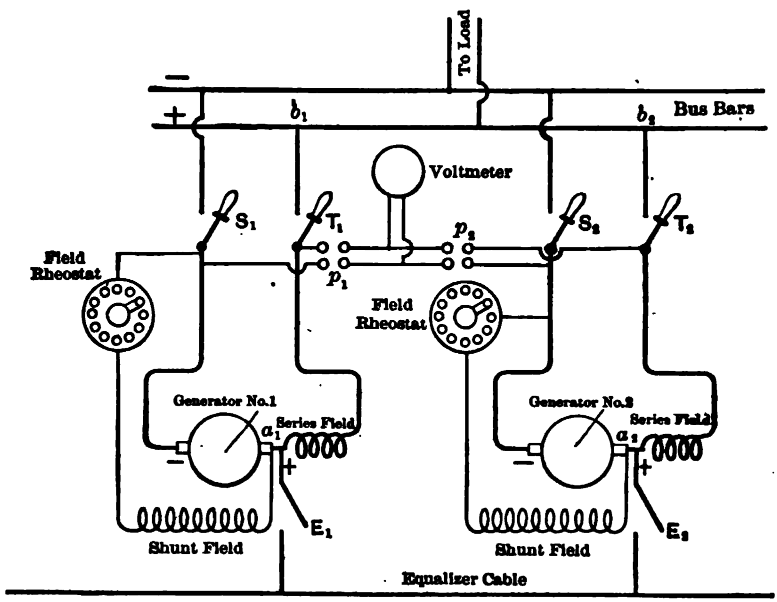

FIG. 204. Two compound-wound generators in parallel.

is open so that there is no equalizing connection, and assume that for some reason one of the machines, for instance No. 2, gives a slightly higher induced e.m.f. The result would be that this machine would take a slightly larger share of the load than No. 1; therefore a larger current will flow through the compounding winding of No. 2 than through that of No. 1. The e.m.f. of No. 2 will thereby be *still more increased*, and the share of load of the other machine decreased. This will continue until one of the machines carries the whole load, while the other machine runs at no load. After this, unless the machines are provided with reverse-current circuit breakers, generator No. 2 will

reverse the current in No. 1 and will drive it as a motor. Such an incident would do no harm to a shunt machine, as was mentioned above; but with a compound-wound machine the reversed current flowing through the series field weakens the total field, and the machine begins to run faster and faster, driving its prime mover. This causes the other machine to become overloaded, and it slows down. Now machine No. 1, having a higher e.m.f. because of a higher speed, causes a sudden rush of current into the line and into the other machine; the phenomenon repeats itself with the machines exchanging their relation of driver and driven.

237. Action of the Equalizer.—Whether the above description of "pumping" between two compound-wound generators is exactly correct or not, experience shows that two compound-wound machines do not work satisfactorily without an equalizer between the points a_1

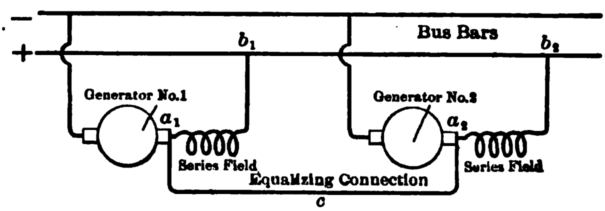

FIG. 205. Diagram illustrating the use of an equalizing connection between two compound-wound generators operating in parallel.

and a_2; the load is distributed unevenly between the machines, from moment to moment, and the current is easily reversed. The action of the equalizer is as follows (Fig. 205): Suppose, as before, that for some reason the induced e.m.f. of machine No. 2 is higher and therefore the current supplied by it larger than that of machine No. 1. This tends to make the ohmic drop between a_2 and b_2 larger than that between a_1 and b_1; but, with an equalizing cable of a negligible resistance between a_1 and a_2, this is impossible, and thus part of the current of machine No. 2, instead of flowing from a_2 to the positive bus-bar directly through b_2, flows to the same bus-bar through the equalizer c and the series winding of machine No. 1. Therefore, the field of machine No. 2 is strengthened *less* than it would be without the equalizer; at the same time the field of the weaker machine, No. 1, is strengthened by the excess of the current of the other machine; machine No. 1 is thus helped to keep up its voltage. In short, *the equalizing connection prevents the currents in the series fields of two or more machines from differing widely from each other, however different their armature currents may be.* **Therefore,**

when connected by an equalizing bus-bar, different machines cannot have widely different voltages; cannot easily have the load disproportionately distributed, and the more remote becomes the possibility of one machine pumping power back into the other machine.

Two or more *identical* compound-wound machines, provided with an equalizer cable, as in Fig. 204, distribute the current among themselves equally well at all loads. A difficulty arises, however, when the machines have *different characteristics*, as was explained in the case of shunt-wound generators. The two conditions under which two compound-wound machines of different type can be satisfactorily operated in parallel are as follows:

(1) Both machines must have the same degree of compounding, or over-compounding, when running separately. If such is not the case, the machine which has a higher degree of compounding will take a larger share of the total output, as the load increases, because its induced e.m.f. will be higher than that of the other machine. The equalizing connection cannot remedy this fault.

(2) When each machine is delivering its proper share of load, the drop between a_1 and b_1 must be equal to that between a_2 and b_2; otherwise an equalizing current will flow through the equalizer; this would be wrong when the machines are delivering each the right current. As a general rule, the resistances $a_1 b_1$ and $a_2 b_2$ do not satisfy this requirement, and it becomes necessary to introduce some artificial resistance into one of the circuits. Then the machines divide the current properly under all conditions of load.

238. Directions for Connecting in Parallel.—Let machine No. 1 be supplying the load alone (Fig. 204), and suppose it to be required to put generator No. 2 in parallel with it. The main switches S_2 and T_2 are open, as well as the equalizer switch E_2. First, machine No. 2 is excited so as to give its full voltage; then the switches E_2 and T_2 are closed in order to cause part of the current of machine No. 1 to flow through the series field of machine No. 2. Then, after the voltage of machine No. 2 is properly adjusted to that of the bus-bars, the last switch S_2 is closed and the excitation brought up so as to distribute the load properly between the machines. In disconnecting one of the machines the switches must be opened in reverse order.

With large machines it is desirable to have three separate switches, as described above. With medium size machines two switches connecting the machine to the bus-bars can be united into one double-pole switch, though in this case the machines cannot be thrown in parallel as smoothly, because the main circuit becomes closed before the field is properly adjusted. In inexpensive isolated plants three-pole switches

are sometimes used, combining all the three switches in one; with small machines a momentary rush of current is not considered harmful.

239. EXPERIMENT 11-G. — Operating Compound-Wound Generators in Parallel. — The student is given two D. C. generators of somewhat different characteristics; the machines may have been previously provided with a series winding, or the student himself may be expected to put it on. As is explained in §§ 236 to 238, three conditions are necessary in order that the machines may operate satisfactorily:

(1) An equalizing connection must be provided.

(2) Both machines must have the same degree of compounding or over-compounding when running alone.

(3) Voltage drop in $a_1 b_1$ must be equal to that in $a_2 b_2$ (Fig. 204).

First try to run the machines without any of these conditions being fulfilled and see what occurs as the load is varied. Then introduce the necessary modifications, one by one, and observe the improvement in operation. Try to obtain a satisfactory operation at all loads, and take a curve showing the division of the load between the two machines.

The performance is considerably influenced by the resistance of the equalizer wire. The lower this resistance the better is the equalization of exciting currents and therefore the more satisfactory the operation of the machines. Take several readings at a constant load but with different resistances in the equalizing circuit, so as to observe the influence of this factor.

THREE-WIRE SYSTEM.

240. There are cases in which it is advantageous to distribute direct-current energy by three wires instead of two (Figs. 206 to 208). The two outside wires are the main wires; the middle conductor merely takes up the unbalanced part of the load. The three-wire system is used in two principal cases:

(1) On lighting circuits, where the economy in copper thus obtained warrants the complication.

(2) In shops where variable-speed motors are used.

In three-wire lighting circuits the lamps are connected between each of the outside wires and the middle wire (Fig. 209). The voltage across the outside mains is about 220 volts, and the copper economy corresponds to this pressure; at the same time standard 110-volt lamps are used. Equation (1) in § 447 shows that the weight of copper with the same power W is inversely proportional to the square of

the transmission voltage. The cross-section of the middle conductor is usually not more than 50 per cent of that of the outside wires, so that even the addition of a third wire still leaves a considerable margin of economy, as compared to an ordinary 110-volt two-wire distribution.

The use of the three-wire system for variable-speed drive is illus-

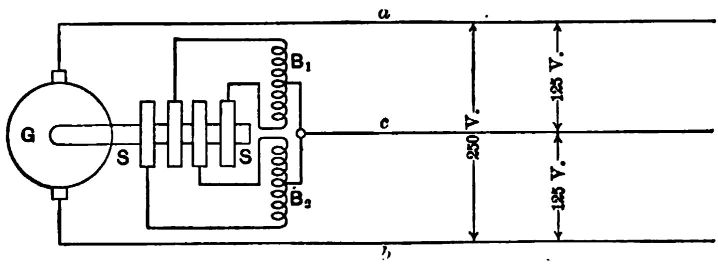

FIG. 206. Dividing line voltage in two by means of balancing coils.

trated in Fig. 223. The motor armature may be connected either across 110 volts or across 220 volts, giving half speed in the first case and full speed in the second case. The same results could be obtained on the 220-volt circuit by inserting some resistance into the armature circuit; but this would be too wasteful of energy, and, moreover, the speed would fluctuate with the load.

The details of the three-wire system and the numerical relations are explained in the following articles.

241. Methods for Dividing Voltage.—The two outside wires in the

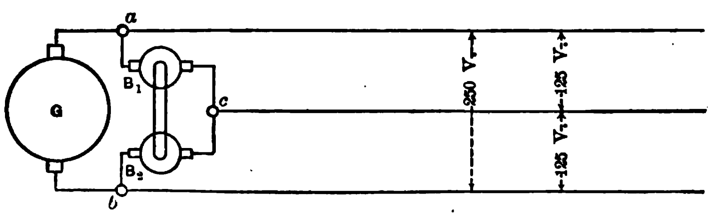

FIG. 207. Dividing line voltage in two by means of a motor-generator called balancer set.

three-wire system are connected to the terminals of the main generator; special devices are used for dividing the voltage in two, so as to obtain a point for connecting the middle conductor. The methods in common use are:

(1) Balance coils (Fig. 206).

(2) Motor-generator, or balancer set (Figs. 207 and 209).

A storage battery may also be used for dividing the voltage, as shown in Fig. 208, but a comparatively high cost and depreciation prevent the universal application of storage batteries for this service.

The balance coils (Fig. 206) are ordinary reactance coils, or auto-transformers, provided with taps B_1, B_2 in the center. The generator G has four slip-rings S, S, connected to four equidistant points of the armature winding, as in a two-phase rotary converter (§ 586). The balance coils are connected as in the quarter-phase system, Fig. 402, and the middle wire c is connected to the neutral point of this polyphase system. This neutral point being symmetrically situated in regard to the outside wires a and b on the direct-current side, its potential is midway between the potentials of these wires, and thus divides the voltage into two equal parts. The energy consumption in the balance coils is small, their inductance being large as compared to their resistance.

Instead of two coils and four slip-rings, three coils and three slip-rings are sometimes used in regular three-phase Y-connection (Figs. 405

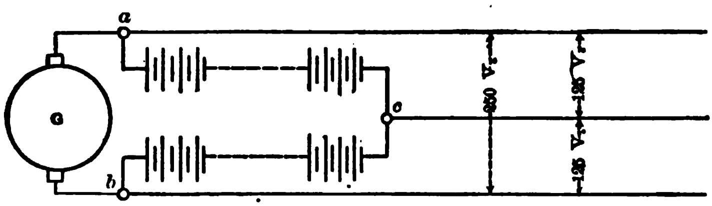

FIG. 208. Dividing line voltage in two by means of a storage battery.

and 436). The middle conductor is connected to the neutral point of Y. This system is particularly well adapted for use with rotary converters, because they are regularly provided with slip-rings. No balance coils are needed in this case, the neutral point being obtained on the main transformers.

The balancer set (Figs. 207 and 209) consists of two identical shunt-wound machines, B_1 and B_2, of comparatively small capacity. The armatures are connected in series electrically, and the machines run idle between the two outside wires; they must be mounted on the same shaft, or belted together. The middle wire is connected at c, between the two armatures.

The machines being identical, excited to the same point, and run at the same speed, the voltage is naturally divided at c into two equal parts. When the load becomes unbalanced, one of the machines runs as generator, the other as motor; the voltages still remain approximately the same, the induced e.m.f.'s being the same. The details of distribution of currents are explained in the next article.

An advantage of balance coils over a motor-generator set is that the former are less expensive, and, being stationary, require but slight attention. On the other hand, a three-wire generator with slip-rings is more expensive than an ordinary two-wire machine. Here, as in most practical problems, the preference is given in each particular case to one or the other system, according to local conditions, and the personal views of the engineer who decides the question.

242. Effect of Unbalancing. — The distribution of currents in a three-wire system with unbalanced load is shown in Fig. 209, the voltage being divided by a motor-generator set. It is assumed that 1000 ordinary 110-volt, 16 candle-power incandescent lamps are connected on one side of the line, and 800 on the other side, each lamp consuming one half ampere. This gives 500 amperes and 400 amperes in the two outside conductors; the difference, 100 amperes, returns through the middle wire to the balancer set. The balancer set, not being connected to a prime

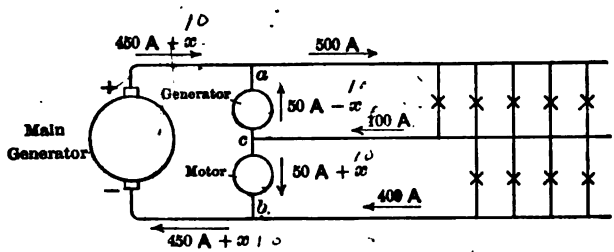

FIG. 209. Distribution of currents in a three-wire system at an unbalanced load.

mover, cannot create energy; it merely equalizes, or transfers it from the less loaded side to the more heavily loaded side. Therefore, if the machines were ideal, 100 amperes would divide into 50 and 50, flowing in the opposite directions, the lower machine running as motor, the upper as generator. The main generator would supply the average load of 450 amperes at 220 volts. With this distribution of currents, the condition is fulfilled at the points *a* and *b*, that the sum of the currents flowing towards a point must be equal to the sum of those flowing from the point.

In reality, the current distribution is somewhat different, because of the losses in the balancer set. A certain current x flows through the set, even when the load is perfectly balanced; this current is necessary for overcoming iron loss and friction in the two machines. Moreover, the main generator has to supply some current for the shunt fields of both machines. Superposing the current x upon the useful currents mentioned above, we get a distribution of currents shown in Fig. 209;

the current in the balancer machine, working as generator, is reduced, that in the motor increased by the amount x. The condition $\Sigma i = 0$ at the points a and b is again fulfilled.

With an unbalancing of currents, the voltages between the middle wire and the two outside conductors become somewhat different; but, with a properly designed balancer set, the difference should not be more than a very few per cent; moreover, it may be corrected to some extent by regulating the field rheostats of the balancer machines. An investigation of current relations in balance coils (Fig. 206) leads to similar results.

243. Efficiency of Balancer Sets. — Referring to Fig. 209, the efficiency of the balancer set is equal to the ratio of the output of the machine working as generator, to the input into the machine working as motor; the excitation losses of both machines should be added to the input. This is according to the standard definition of efficiency of any motor-generator set. It will be easily seen, however, that in the case of a balancer set, the efficiency, according to this definition, becomes negative, when the load is nearly balanced, because then both machines operate as motors. As unbalancing increases, the efficiency gradually rises to zero and then becomes positive. There is no physical contradiction in this result, provided that the actual conditions of the operation of the set are clearly kept in mind.

There is another way of looking at the efficiency of a balancer set, namely, from the standpoint of the three-wire system, taken as a whole. The losses in the balancer set increase the output of the main generator above the useful demand for power; the ratio of this demand to the output of the main generator may be called the efficiency of the three-wire system, with reference to the balancer set.

To illustrate the two above definitions of efficiency, assume that the no-load current of the balancer set, x, is 10 amperes (Fig. 209), and that the field circuit of each machine consumes 2 amperes, both fields being connected in parallel, across the outside conductors.

The efficiency of the motor-generator set itself, according to the first definition, is

$$\frac{(50 - 10)\,110}{(50 + 10)\,110 + (2 + 2)\,220} = 70.6\%.$$

The efficiency of the three-wire system itself, according to the second definition, is

$$\frac{500 \times 110 + 400 \times 110}{(450 + 10 + 2 + 2)\,220} = 97\%.$$

Both expressions have definite physical meaning, and both are used according to the conditions of a problem. If a greater accuracy is required, copper loss in the armatures of the balancer set, and the resulting unbalancing of voltages, must be taken into account in the above expressions for efficiency.

244. EXPERIMENT 11-H. — Study of a Symmetrical Three-Wire System.— Wire up the generator and the balancer set, as in Fig. 207, and provide variable resistances, to be used as a load. Load up one side of the line until the balancer runs as nearly as possible at its full rated capacity. Note the input and the output of the motor and generator constituting the balancer set, voltages on the loaded and unloaded sides of the line, speed of the set, currents in the three line wires, and the field current of the balancer machines. Then begin loading the other side of the line, keeping the load on the first side constant. As the unbalancing decreases, the balancer load also decreases, though the total load on the line increases. Take readings as indicated above with different degrees of unbalancing, until the load on both sides is the same, and the balancer runs idle. Increasing the load further merely reverses the conditions in the balancer; the machine which was running as motor begins to run as generator, and vice versa.

If a generator with slip-rings is available, or a rotary converter, a three-wire system with balance coils (Fig. 206) may be realized. It is not absolutely necessary to have three or four slip-rings; if only two slip-rings are available, the neutral point may be obtained with one balance coil. In fact, it is desired that the student investigate the effect of using only one balance coil instead of two. With a three-phase rotary converter, three balance coils are connected in Y, and the middle wire connected to the neutral point. The same load experiment should be performed with balance coils as with the motor-generator set. Note, that balance coils consume a magnetizing current, which is an alternating current, and cannot be detected by ordinary moving-coil ammeters (§ 37).

Report. Draw a diagram of actual connections. Plot to amperes in the main generator: the currents in the two outside wires and in the neutral, the voltages, the generator output, and the currents in the balancer armatures and fields; also the speed of the set. Figure out the efficiency of the balancer set and of the three-wire system, as in § 243. Give similar results for the run in which balance coils were used.

245. Unsymmetrical Three-Wire System.—When a three-wire system is used for variable-speed drive, it is not necessary to have the voltage divided into two *equal* parts; in fact, by making the system

unsymmetrical a wider range of speeds can be obtained. Such an unsymmetrical, or, as they are improperly called, "unbalanced" system, is shown in Fig. 210. The two machines, constituting the balancer set, are wound for different voltages, so that the total pressure of 250 volts is subdivided into 90 volts and 160 volts. With this system the armature of a motor can be connected on either 90, 160 or 250 volts, which gives a ratio of about 3 : 1 between the lowest and highest speeds. If, in addition, field control is used, by which the speed of the motor is increased twice, a total speed range of 6 : 1 may be had, instead of 4 : 1, as with the ordinary symmetrical three-wire system. The disadvantages

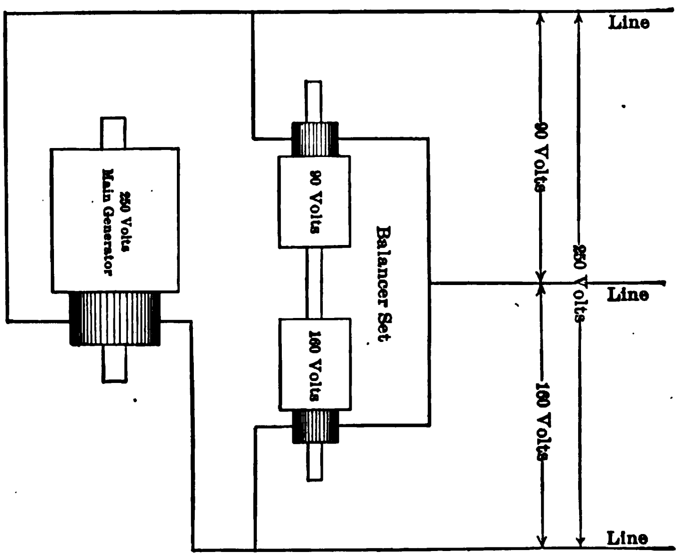

FIG. 210. An unsymmetrical three-wire system for variable-speed drive.

of this system, as compared to the ordinary three-wire system, are: more expensive wiring because motors take a heavy current at low voltage; the system is unsymmetrical and therefore more difficult to supervise, and the balancer set is more expensive. The application of this system has thus far been a limited one, though it may be profitably used in large repair shops where a wide range of speed of machine tools is of prime importance.

246. EXPERIMENT 11-I. — Study of an Unsymmetrical Three-Wire System. — Same directions as in § 244.

247. Four-Wire System. — Some companies have gone so far as to use a *four-wire* unsymmetrical system, in order to get a still wider varia-

tion of speed of the motors. One of these systems, which has been practically applied in a few cases, is shown in Fig. 211. The balancer set consists of three direct-connected machines, *A*, *B* and *C*. Two of these machines may be combined into one two-commutator machine; this makes the set less expensive and less cumbersome. It will be seen that with such a system six different combinations of voltages, and therefore six different speeds, are possible, without field control. The

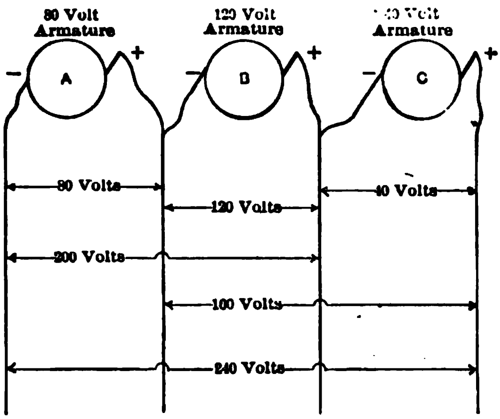

FIG. 211. An unsymmetrical four-wire system for variable-speed drive.

ratio of the highest to the lowest speed is as 240 : 40 = 6 : 1. By using field control, the range of speeds may be about doubled. The complication and the expense of a four-wire unsymmetrical line are such as to justify the use of this system in exceptional cases only. However, the more expensive labor and machinery become, the greater field may be opened for such multivoltage systems, as they permit a considerable increase in the output of tools. On the other hand, the use of motors with compensating poles (§ 262) permits of a wide range of speeds, without the complication of a four-wire system.

248. EXPERIMENT 11-J.—Study of a Four-Wire System.—Same directions as in § 244.

Note. For troubles in operation of direct-current machines, and their detection, see §§ 267 to 271.

CHAPTER XII.

DIRECT-CURRENT MOTOR — OPERATING FEATURES.

249. DIRECT-CURRENT machines, such as are shown in Fig. 192 and described in § 221, are *convertible*, that is to say, they may be operated either as generators or as motors. When such a machine is driven by a source of mechanical power (prime mover) it is operating as a generator and delivers electrical energy. Conversely, when electrical energy

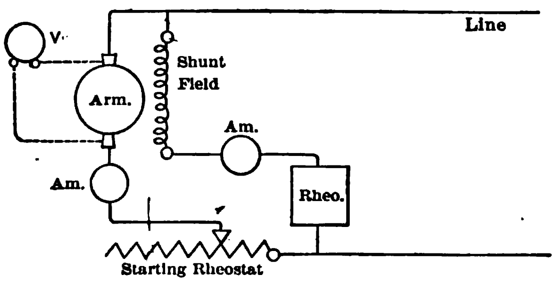

FIG. 212. Diagram of connections of a shunt-wound motor.

is supplied to the machine it runs as a motor and is capable of developing mechanical energy available at its shaft.

This convertibility is a direct result of two fundamental laws of electromagnetism; viz.: (1) when an electrical conductor, forming part of a closed circuit, is moved across a magnetic field, currents are induced in the conductor such as to oppose the motion; (2) when a current is sent through a conductor located in a magnetic field, it tends to move out of the field. In the first case the conductor acts as an element of a generator, in the second as an element of a motor.

250. Types of Motors. — Two types of direct-current motors are most commonly used in practice—shunt-wound motors (Fig. 212) and series-wound motors (Fig. 213). In the shunt-wound motor the field winding is connected directly across the constant voltage supply circuit, so that the magnetism of the motor is practically constant at all loads. In the series-wound motor, the field winding is in series with the armature circuit; as the load increases, the current taken by the motor also

increases, this increased current strengthening the magnetic field of the motor.

There is a marked difference in the performance of these two types of motors, and each type has a field of application of its own. The shunt motor is essentially a constant-speed motor, while the speed of the series-wound motor increases as the load decreases. A theoretical exposition of this is given in the next article, which explains the facts observed experimentally. Shunt-wound motors are used for machine-tool drive, and for driving various machines in textile and other industries, where a constant, or nearly constant, speed is required, independent of the load. Series-wound motors are used in railway, crane and hoisting work, where a heavy starting torque is necessary, and where the motors have to be frequently started and stopped. In these cases it is

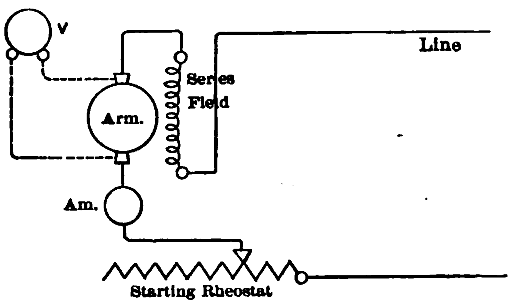

FIG. 213. Diagram of connections of a series-wound motor.

desirable to have a motor which automatically slows down as the load increases, in order not to have too large fluctuations in power demand. In some special cases motors are desired, with characteristics intermediate between those of the two above-mentioned types. Such motors are provided with both series and shunt field windings, and are called compound-wound motors. They are used with elevators, also for driving planers, punches, etc.

In operating electric motors, starting and regulating rheostats are required; these devices are described in Chapter XIX (Motor Starters and Regulators). It is recommended that the student perform one or two of the first experiments of that chapter before beginning the brake tests described in this chapter.

251. Field Strength and Speed. — The difference in the behavior of shunt and of series-wound motors under various loads can be explained as follows: When the armature of a motor is revolving, a counter-electromotive force is induced in it by the magnetic field of the machine

This e.m.f., e, is smaller than the applied voltage E by the amount of the ohmic drop IR in the armature and brushes, or

$$e = E - IR.$$

In commercial motors the term IR amounts to but a very few per cent of E, in order to keep the efficiency of the motor sufficiently high. Therefore *e is approximately equal to E*, or the counter-electromotive force induced in the armature is approximately equal to the applied voltage. On the other hand, this counter-e.m.f., according to the fundamental law of induction, is proportional to the magnetic flux of

R.P.M.

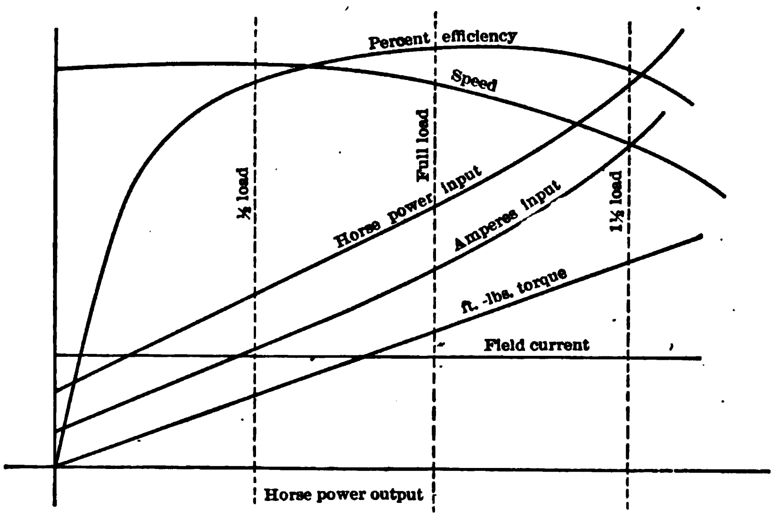

FIG. 214. Performance curves of a shunt-wound motor.

the machine, and to the speed at which the armature conductors cut the flux. Thus

$$e = C.\ \overset{\phi}{\cancel{N}}n. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where C is a constant, N is the useful flux of the machine, and n is its speed. The e.m.f. e being approximately constant, so long as the voltage at the armature terminals is constant, the product, flux times speed, in this formula is also constant.

In a shunt-wound motor (Fig. 212) the fields are separately excited, so that the flux *is* constant, and does not depend on the load. Therefore, the speed of such motors is also approximately constant. In series-wound motors (Fig. 213) the field strength depends entirely upon the load, since the exciting winding is connected in series with the main

circuit. As the load decreases and the motor begins to consume less power, a smaller current flows through the field winding, and the field is weakened. But, according to the equation (1), the weaker the field, the higher the speed of the motor. For this reason a series motor runs faster the lighter the load. A series motor should never be connected to the supply without any load; it will run away, unless a sufficient resistance is connected in its circuit.

The difference in characteristics of the shunt and the series motor is made clearer by a study of their performance curves, shown in Figs. 214 and 215, — particularly by a comparison of the speed curves.

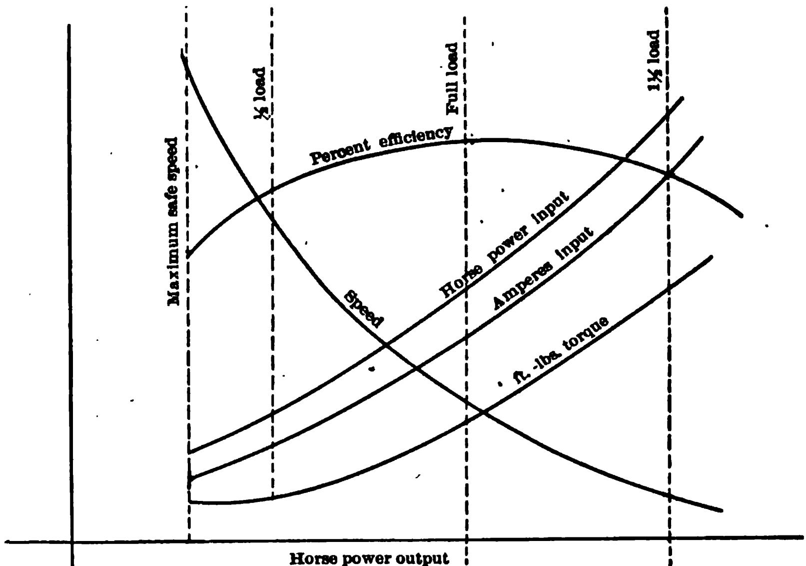

FIG. 215. Performance curves of a series-wound motor.

252. Speed Control.— It has been shown above that the speed of a *shunt-wound motor* remains approximately constant, as long as the field excitation is constant. If, however, it is desired to increase the speed, this can be done by weakening the field of the motor by means of the field rheostat. When the field current is reduced, the counter-e.m.f. is also reduced the first moment; this causes a rush of current into the armature, and an excess of power above that necessary for carrying the load. This excess of power accelerates the motor, until the counter-e.m.f. has increased sufficiently to allow but the normal current to flow through the armature.

This method of speed control is actually used, — for instance, in machine-tool drive. A limit to weakening the field is imposed by

sparking at the brushes, for, with a weak field, the armature action becomes more prominent and distorts the field; the currents in the coils short-circuited under the brushes become excessive, and cause a destructive sparking at the commutator.

The value of the armature reaction depends on the position of the brushes; therefore the speed of the motor may be varied within certain limits by merely shifting the brushes. No considerable speed variation can be obtained by this means, since the motor begins to spark as soon as the brushes are shifted too far either way from the right position, but this method is convenient for adjusting a speed to an exact value, after an approximately right speed has been obtained by the regulating rheostat.

Speed of a shunt motor is lowered by reducing the voltage at the armature terminals; this follows directly from equation (1). Inserting resistance in the armature circuit is seldom done except with very small motors, the method involving considerable waste of energy. The voltage may be varied economically by having the motor connected to a three-wire (three-voltage) supply (see §§ **240** and **245**).

Speed of a *series motor* may be increased also by weakening the field; this is done by providing a shunt around the field winding. This method has been used to some extent on street-car motors, where the car had to run on long level stretches. This expedient has been abandoned, because weakening the fields increases the effect of armature reaction and causes the motors to spark. *Compensated* railway motors are now coming into use, in which the armature reaction is overcome, and the method of shunting fields is coming into use again, especially on interurban roads, where considerable time can be saved by running long stretches at a high speed.

To reduce the speed of a series motor, resistances are inserted into the armature circuit. This method is used in practice with railway and crane motors, where economy is not so important because of an intermittent service, but where speed control is very essential. It is also possible to reduce the speed by shunting the armature by a resistance, so as to have a comparatively strong field with small armature currents. This method is hardly ever used in practice, except for tests (see § 292).

253. Prony Brake. — The performance curves shown in Figs. 214 and 215 are obtained by loading the motor and measuring input, output and speed. The simplest device for loading motors is a Prony brake (Fig. 216); it is extensively used with small and medium sized motors. In the form shown in the sketch, it consists of an iron band *ab* lined with soft wood, or with heavy canvas. The band embraces

the pulley P of the motor, and is fastened to the beam k, the end of which rests on the scale S.

When the motor revolves, friction is developed between the lining of the brake and the pulley; the power of the motor is thus converted into heat. The brake pressure is regulated by the hand-wheel h, and in this way any desired load is obtained. The turning moment, or the *torque*, as it is called, is measured on the scale.

In most cases it is necessary to carry away the heat developed by friction, in order to prevent burning of the brake lining. The pulley, shown in the sketch, is cooled by a stream of water from the pipe w (see cross-section to the left); water is thrown by centrifugal force against the inner surface of the face of the pulley; the flange prevents it from being spilled.

If P is the net pressure on the scale at the end of a lever l feet long,

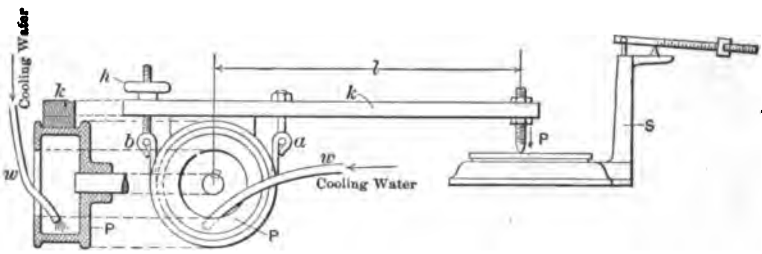

FIG. 216. A Prony brake with water-cooled pulley.

the pressure at the end of a lever 1 foot long is Pl lbs.; consequently the work in ft.-lbs., performed during one minute, is $Pl.\,2\pi n$, where n is the number of revolutions of the motor per minute. The same in horse-power is

$$\frac{Pl.\,2\pi n}{33000},$$

or

$$\text{horse-power} = \frac{Pln}{5252}.$$

This is the common expression for figuring the output of a motor from a Prony brake test.

For loading very large motors the so-called water-brake is used; power is absorbed in it by driving water through paths of high resistance. The resultant friction heats up and even evaporates the water, while cold water is continually being supplied from the mains.

Eddy-current brakes are used to some extent with small motors. Such a brake usually consists of a copper disk mounted on the motor

shaft, and of a set of electromagnets placed near the disk and supported from knife-edges, or ball bearings. When the motor revolves, eddy currents are induced in the disk as it cuts through the field produced by the electromagnets. The electromagnets tend to follow the disk, as in the classical Arago experiment, but are prevented by a lever which rests on a scale, as in Fig. 216; the pressure on the scale measures the torque. Load is varied by regulating the exciting current; artificial cooling of the disk is sometimes necessary. Eddy-current brakes give a steadier load than is possible with mechanical brakes.

254. Transmission Dynamometer.—An objection to the Prony brake is that load is not quite steady while speed is being measured;

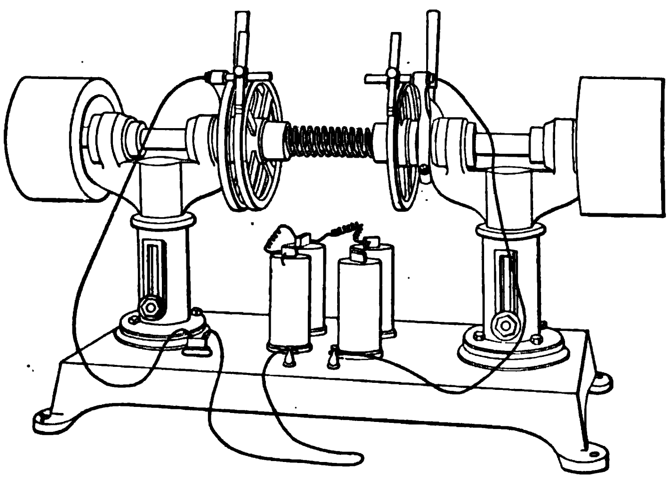

FIG. 217. A transmission dynamometer (see Fig. 218).

this limits the accuracy of the test. Another disadvantage is that a considerable amount of energy must be dissipated in a limited space. It is much more convenient to load the motor on an electric generator, a pump, a blower, etc., provided that the output of the motor can be readily measured. One method is to use a generator, the efficiency of which is known from a previous calibration. Another way is to connect the load machine to the motor under test, through a transmission dynamometer, such as is shown in Figs. 217 and 218. The dynamometer does not absorb the power, but merely measures the torque between the driving and the driven shafts.

The torque is measured by the torsion spring previously calibrated in pounds. The difficulty in former dynamometers consisted in accurately measuring the angle of torsion of the spring, with the shafts

revolving. This difficulty is ingeniously solved in the dynamometer, shown in the sketches, by measuring this angle electrically. An electric circuit is established through a few dry cells, a telephone receiver and the dynamometer spring, through two brushes and the contacts, — all clearly seen in Fig. 218.

When the machines are stationary, the brushes are in such a position, that when moved around together they come under the contacts simultaneously, and the circuit is closed; this is recognized by a click in the telephone. When the set is revolving, carrying a load, the spring is twisted, and the contacts are no longer closed simultaneously; the click in the telephone disappears. The left-hand brush is then shifted along the contact ring, until the click is again heard; the angle is read on the stationary index, and is evidently equal to the angle by which the

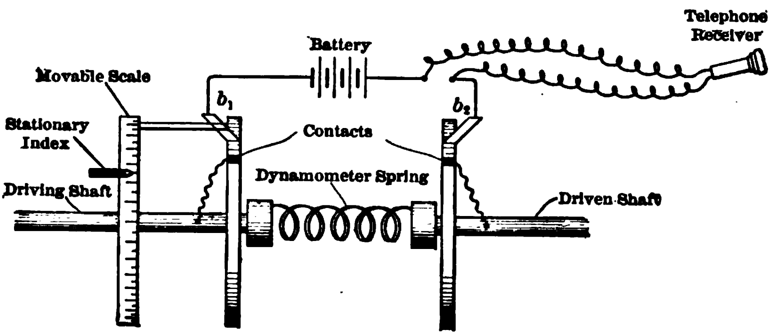

FIG. 218. Electrical connections in the dynamometer shown in Fig. 217.

spring was twisted. The power transmitted is calculated from the formula:

$$\text{horse-power output} = \text{constant} \times \text{angle} \times (\text{r.p.m.}).$$

The spring is previously calibrated by weights, and the torsion constant calculated. Several springs of different rigidity are used with the same dynamometer, to increase its useful range. The dynamometer may be adapted to be used with machines direct-connected; or else, is provided with a pulley, and the load machine is belted to it.

255. EXPERIMENT 12-A. — Brake Test of a Shunt Motor. — The purpose of the experiment is to obtain performance curves such as are shown in Fig. 214. The motor should be wired up, as shown in Fig. 212; one independent circuit includes the field winding with its regulating rheostat, and an ammeter; the other circuit is formed through the armature of the motor, with its starting and regulating rheostat,

and an ammeter. A voltmeter *V* is connected across the armature, for measuring the pressure at which the machine operates. Either a Prony brake (§ **253**), or a transmission dynamometer (§ **254**) may be used for loading the motor.

Begin the test with the highest load, say 25 per cent overload; read armature amperes, field amperes, terminal voltage, speed, and brake load. Then gradually reduce the load to zero, taking a sufficient number of readings (from 8 to 10) for plotting curves. The field current and the terminal voltage must be kept constant throughout the whole test. The readings may be conveniently recorded on such a data sheet as is here shown.

	Arm. Amps.	Field Amps.	Volts.	R. P. M.	Torque Lbs.
Inst. No.					
Const					

Take a few points with field current 10 and 20 per cent below normal (see § **252**). Also make runs with line voltages, say 10 per cent above and a like amount below normal, in order to see the influence of this factor on the performance of the motor.

Report. Plot performance curves, as shown in Fig. **214**. On the same curve sheet plot the readings taken with lower field currents; also those corresponding to the various voltages of the supply. Explain the results.

256. EXPERIMENT 12-B. — Brake Test of a Series Motor. — The purpose of the experiment is to obtain performance curves for the series motor, as shown in Fig. **215**. The experiment is conducted in much the same way as the preceding experiment, except that precautions should be taken to prevent the motor running away. With a shunt motor, the brake can be safely released, since the speed of the motor is practically the same at no load as when loaded. In a series motor the speed increases enormously, as soon as the load is taken off, and either the armature, the commutator, or the bearings are sure to be damaged, if the motor be allowed to run at this speed. For this reason, *always open the circuit before releasing the brake;* or at least have a sufficient resistance inserted into the circuit, to keep down the speed.

As an additional precaution against the motor running away, an *under-load circuit-breaker* should be connected into the circuit; when the load is taken off, the current falls below a certain limit, and this device automatically opens the circuit. The student should not, however, rely absolutely on this circuit-breaker. It may "stick" just when it is necessary for it to act. It is best to have one man of the section stand near the main switch, and open the circuit if the motor reaches a dangerous speed.

The motor is wired up in series with starting and regulating rheostats and an ammeter. A voltmeter is connected across the motor terminals, and the voltage should be kept as nearly constant as possible. Begin the test as usual with the highest load. Take readings of amperes, volts, speed and torque. Then reduce the load by approximately equal steps, until the safe limit of the motor speed is reached.

Take a few readings with the field weakened by 10 and 20 per cent; also with the armature shunted by the same amounts (see § 252). Take a few runs with the supply voltage about 10 per cent above and below rated. The report is similar to that of the preceding experiment.

COMPOUND-WOUND MOTORS.

257. An ordinary shunt-wound motor is entirely satisfactory in most cases where an approximately constant speed is required with variable load, as, for instance, in machine-tool drive. There are, however, cases of considerable practical importance, where the characteristics of the shunt motor can be improved by providing it with an additional series winding, similar to that of compound-wound generators. Such motors are called compound-wound motors; the series winding can be arranged either so as to strengthen the field produced by the shunt winding, or to weaken it. The first is called *cumulative* compounding; the second, *differential* compounding.

258. Cumulative Compounding. — Cumulative compounding of shunt motors is used when the motor is regularly subjected to heavy but short overloads, for instance in driving punch and shears, planers, in elevator work, etc. Each time when the punch touches the sheet of metal, or the planer tool begins a new cutting stroke, there is a rush of current into the motor armature. This affects the generator, affects the lamps and other motors by producing a fluctuating voltage, and is detrimental to the motor itself, on account of excessive heating and sparking.

This rush of current into the armature could be reduced if the field were automatically strengthened each time when an overload occurs.

The reason for this is that the torque of a motor, or the attraction between the armature and the field, is proportional to the product, "field × armature current;" if the field becomes stronger when an overload occurs, the armature current does not need to be so large for the same torque. This is precisely what the cumulative compound winding accomplishes: when an increased current flows through the armature it has to flow through the series field winding, and thus automatically strengthens the field.

Suppose, for instance, that at times the motor has to overcome a torque six times larger than that at which it is running most of the time. With a constant field, as in the shunt motor, the armature current must increase *six* times. With a compound winding, *three* times the normal current may be sufficient, because the field strength increases as the current increases; this stronger field times the triple current may give six times the normal torque. For this reason motors used on widely fluctuating loads are often provided with a cumulative compound winding. Of course, such a motor slows down more than a shunt motor would do, when the load increases, but this is not objectionable in most cases.

259. EXPERIMENT 12-C. — Effect of Cumulative Compounding of Motors.—The experiment is conducted essentially as an ordinary brake test on a shunt motor (see § 255). In order to see more clearly the influence of the compound winding, it is advisable to provide different degrees of compounding, either by dividing the series winding into sections, or by connecting a variable shunt around it. The test itself should be conducted as follows:

(*a*) Begin with the heaviest load and no compounding, that is, use the shunt winding only; adjust the brake so as to have the armature current, say 25 per cent, greater than its normal rating. Read amperes, volts, speed, field current, and torque, as in a regular brake test.

(*b*) Introduce part of the series winding into the circuit, and take readings with the same brake torque as before. Increase the compounding action, with the same load torque, and read as before; repeat under new conditions, etc., taking altogether four or five sets of readings. This will illustrate the action of the compound winding at a certain torque.

(*c*) Take a lighter load and again get readings with different degrees of compounding; continue the same process down to no load. The results obtained will show the influence of compounding on the current taken by the motor, on its efficiency, and on speed variations as compared to an ordinary shunt motor. If possible, the brushes should not

be shifted during the whole test, as this would change the armature reaction, and consequently the speed of the motor. Should it be necessary to move the brushes because of an excessive sparking, this must be noted in the results, and a record made of the number of commutator bars by which the brushes were shifted.

(*d*) The behavior of the motor under actual fluctuating load conditions should be observed, both with and without the series winding. A lathe is convenient for this purpose; a piece of work is put in it, of such a shape that the tool cuts only part of the revolution, thus giving the motor a fluctuating load. No *exact* measurements can be attempted under these conditions, except a special recording ammeter and a tachograph are available. In the absence of such, the current is read every few seconds, and speed observed as closely as possible with an ordinary tachometer. See also the arrangement for recording variable load, described in § 713. The results plotted to time as abscissæ will give an approximate idea of the general performance of the motor under sudden overloads, with and without compound winding.

Report. The results of the regular load test should be plotted to either torque, horse-power output, or armature amperes as abscissæ, all on the same sheet, so as to show the influence of compounding on speed, efficiency, input and output of the motor.

260. Differential Compounding. — In contra-distinction to the cases, in which cumulatively compounded motors should be used, there are cases, in which a motor is hardly ever subjected to sudden heavy over-loads, but where an absolutely *constant speed at all loads* is very essential. This is the requirement, for instance, in some textile factories, where one motor operates a large number of spinning or weaving machines. The speed of the motor should not depend on the number of machines in actual operation, for every change in speed affects the quality or the design of the product. Motors used for such purposes are usually provided with a demagnetizing, or *differential* compound winding. The reason for this is as follows:

A shunt-wound motor usually slows down a few per cent as the load increases; in order to bring up the speed to its former value, it is necessary to weaken the field of the motor by a field rheostat. In a differentially-wound compound motor the same is done automatically: When the load increases, the armature current also increases; thus a larger current flows through the series winding; as the same is connected so as to oppose the shunt-field winding, the field strength is reduced, and the motor speeds up. By properly adjusting the number of turns of the series winding, a fairly constant speed can be secured throughout the working range of the motor. By further increasing

the number of turns an over-compounding is obtained, that is to say, the speed of the motor increases with the load. This, however, has so far had but little practical application.

A difficulty in obtaining an absolutely constant speed is caused by saturation in iron. The speed depends on the *flux,* while the compounding action is proportional to the number of *ampere-turns.* When the iron is far from saturation the flux *is proportional* to ampere-turns, so that theoretically a perfectly constant speed may be had at all loads; near saturation this condition does not hold, and a motor compounded so as to give the same speed at full load as at no load, runs at somewhat different speeds at partial loads. This result of saturation is observed in a generator compounded so as to give the same voltage at full load as at no load, but which gives too high a voltage at intermediate loads (Fig. **198**). This effect is more noticeable the nearer the magnetic circuit approaches saturation.

A differentially-wound motor does not start as easily as an ordinary shunt motor. This is due to the starting current weakening the field and so reducing the starting torque. If an excessive starting current is allowed to flow through the series field, the action of the latter may become even stronger than that of the shunt field, and the motor will have a tendency to start in the wrong direction. Therefore, differentially-wound motors are usually provided with a switch for short-circuiting the series winding during the starting period. After a considerable speed has been attained, and the current has dropped to its normal value, this switch is opened, and the motor runs at its rated speed.

261. EXPERIMENT 12-D. — Effect of Differential Compounding of Motors. — The experiment consists in loading the motor, and observing speed variations. A steady load is obtained by means of a generator, or a blower; either of these being preferable to a Prony brake. In order to be able to determine the motor load, the generator, or the blower, must be calibrated, unless a transmission dynamometer is used (§ **254**). If the load cannot be measured, refer motor speeds to amperes input, instead of horse-power output. The test should comprise several sets of readings, at various loads and with different degrees of compounding. From these readings, when plotted as curves, conclusions can be drawn as to the variation of speed with the load; also, the right number of turns in the series winding can be determined. The test should be performed with at least two values of shunt-field current, one value corresponding to the field highly saturated, another with the field considerably weaker, that is to say, at a higher speed. This will show

the influence of saturation of the magnetic circuit on speed regulation.

VARIABLE-SPEED DRIVE.

262. Varying Speed by Field Control. — It is explained in § 252 that the speed of a shunt motor increases as the field excitation

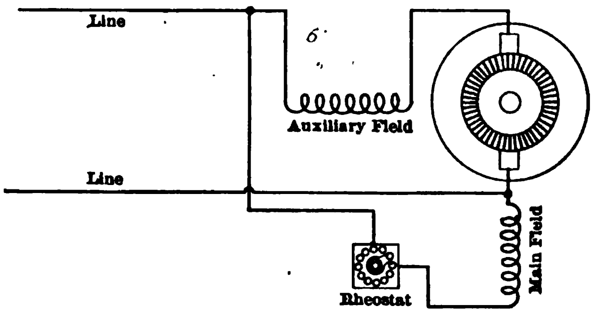

FIG. 219. A shunt-wound motor with a compensating winding for neutralizing the armature reaction.

is weakened, — the limit being usually imposed by sparking at the brushes, due to the increased effect of armature reaction. Therefore, the efforts of designers of variable-speed motors have been constantly directed towards a possible reduction of the armature reaction. This meant, in the first place, a strong and saturated magnetic field, and a comparatively weak armature (as expressed in ampere-turns). The next step was to compensate for the armature reaction by providing an auxiliary field (Fig. 219) with an effect equal and opposite to that of the armature. The coils comprising this compensating field must evidently be connected in series with the armature, so as to give the right number of ampere-turns with varying armature currents. The field frame of a compensated motor is shown in Fig. 220. The four large poles produce the main field (shunt field), the narrow poles constitute the auxiliary compensating field. Such "inter-pole" motors easily give a speed ratio of 4 to 1 by field control, without excessive sparking.

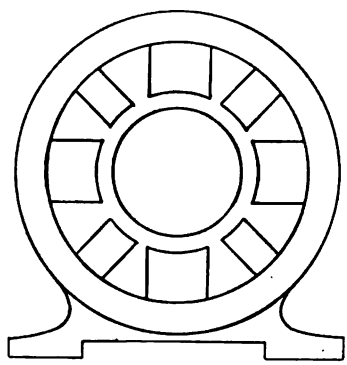

FIG. 220. A four-pole motor frame with compensating poles (interpoles).

The inter-poles, or compensating poles, are now becoming quite popular, and have been applied not only to shunt motors, but to series-wound railway motors as well. They are also used to some extent with direct-current generators, especially those driven by steam-turbines; this is done in order to suppress sparking caused by high frequency of commutation.

The field arrangement of another type of variable-speed motor is shown in Fig. 221 (Stow motor). Instead of varying the field strength

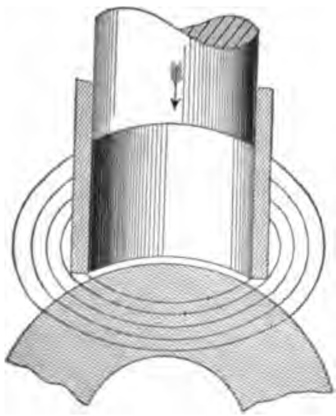

FIG. 221. Pole-piece in a Stow motor; cross-magnetization is reduced by an air column.

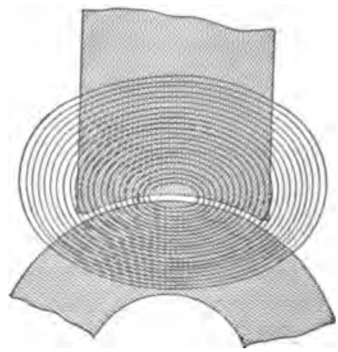

FIG. 222. Pole-piece in an ordinary motor; field distortion is the greatest when the field is the weakest.

by regulating the shunt current, the field is varied in this motor by changing the length of the air-gap. The pole-piece consists of a plunger actuated by a hand-wheel. The higher the pole-piece is raised, the larger is the air-gap, and therefore the weaker is the field (with the same field current). In four-pole motors of this type all the pole-pieces are moved simultaneously by a beveled-gear transmission. The reason why the effect of armature reaction in this motor is reduced at higher speeds may be seen by a comparison of Fig. 221 to Fig. 222, which latter represents the field of an ordinary motor. In the Stow motor, as the air-gap becomes larger, the reluctance of the magnetic path for the distorting lines of force, created by the armature, also increases, thus reducing the harmful cross-magnetization flux. On the contrary, in an ordinary motor field, distortion is greatest when the field is weakest.

In another type of motor, based on a similar principle (Lincoln

motor), the armature is made slightly larger at one end than at the other, and can be shifted along the shaft by a hand-wheel. As it is withdrawn from the pole-pieces, the useful magnetic area decreases; moreover, the air gap increases because of the conical shape of the armature. The result is that the useful flux decreases, and the speed of the motor increases.

263. EXPERIMENT 12-E. — Study of Compensated Variable-Speed Motors. — The experiment consists in a study of the performance of a shunt motor, provided with inter-poles. A Stow, or a Lincoln motor may be studied in a similar way. Either a Prony brake or a calibrated generator may be used as a load. In order to save time and have more runs taken under different conditions, readings on partial loads can be omitted.

(*a*) Start with the heaviest load and the lowest speed possible; read input, output, speed, etc., as in a regular brake test. Reduce the load to about 50 or 75 per cent of the rated capacity of the motor, and take another set of readings. Then run the motor light, with the same field. These three runs will give sufficient information concerning the behavior of the motor with a certain field current.

(*b*) Load the motor again to its full capacity, but at a lower field current (higher speed), and repeat the three runs as before. Repeat at higher speeds, until the limit of speed is reached, beyond which it would not be safe to go, on account of the danger from centrifugal force, and destructive sparking.

Adjust the brake load so as to have the same horse-power output with different values of the field current, in order to get comparable results.*

(*c*) The speed characteristics of a compensated motor depend essentially upon the position of the brushes. Take a few runs with different settings of the brushes, and measure accurately the speed, with the motor running in both directions.

(*d*) Disconnect the compensating winding, and take load readings with the same horse-power output as before, and with the same values of field current. Weaken the field as far as the sparking limit will allow.

Report. Plot to field current as abscissæ: speed and efficiency, with and without the compensating winding. Points on the same ordinates must refer to equal values of horse-power output. Discuss the results.

264. Motors on Three-Wire Systems. — Instead of by field control, speed may be regulated by varying the voltage at the armature termi-

* Variable-speed motors are usually designed to give the same horse-power output at all speeds; this means that the torque must be decreased as speed is increased.

nals. In most cases it would be out of the question to do this regulation by rheostatic control, as it is too wasteful of energy. However, it can be done economically on a three-wire system (Figs. 209 and 223).

A great deal has been written by various authorities on the relative advantages of three-wire systems and field control; as the question now stands, each individual case must be decided according to local conditions. If but a few variable-speed motors are needed, compensated shunt motors with field control are more economical; where a good many motors are to be installed, it becomes a question of dollars and cents, whether (a) more expensive compensated motors should be

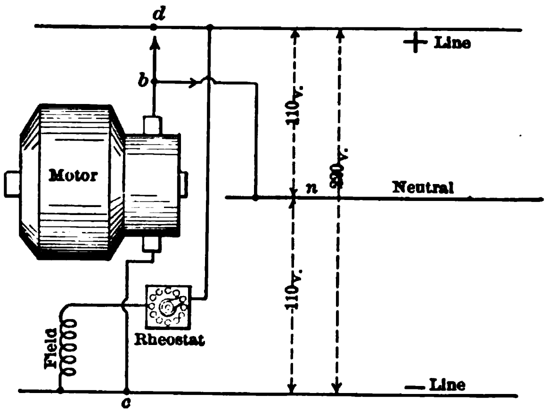

FIG. 223. Motor connected to a three-wire supply.

used, with an ordinary two-wire system; or (b) an extra investment put into the third wire, a balancer set, etc., and standard shunt motors used.

A shunt motor connected to a three-wire system is shown in Fig. 223. The field is permanently connected between the outside wires, but may be varied to some extent by the rheostat in its circuit. The armature may be connected at will, either on half voltage, *cbn*, or on full voltage, *cbd*. To get the lowest speed, say 400 r.p.m., the motor field is fully excited, and the armature connected across 110 volts. By gradually weakening the field, the speed can usually be doubled before difficulties in commutation begin; this gives any desired speed between 400 and 800 r.p.m. After this, the armature is switched on to the full voltage, 220 volts, and the field fully excited; this gives again 800 r.p.m.; then by weakening the field the speed can be brought up

to 1600 r.p.m. This gives the same speed limits, 4 to 1, as with a good compensated motor.

By using an unsymmetrical three-wire system (§ 245), or a four-wire system (§ 247), a still wider range of speed may be obtained.

Instead of a three-wire system, two motors can be used for driving the same tool or shaft; by connecting them in series and in parallel (as in a street car), half speed and full speed can be had. It is even unnecessary to have two separate motors; the two armature windings can be put on the same core and revolve in the same field. This gives the so-called "two-commutator motor" (Fig. 224). When *a* is connected to *b*, the two armature windings are in series, and the motor

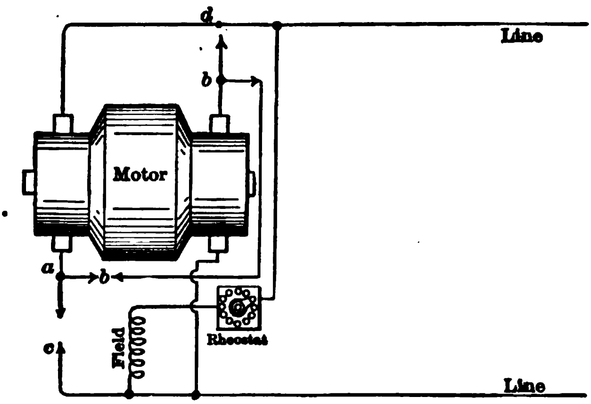

FIG. 224. A two-commutator motor: the armature windings may be connected in series or in parallel.

runs at half speed; when *a* is connected to *c*, and *b* to *d*, the two windings are in parallel, and the motor runs at full speed. The field circuit is provided with a regulating rheostat, by means of which the range of speed is further increased and intermediate speeds are made possible. Such an arrangement may be useful in special cases, but, as a rule, either the compensated motor or the three-wire system is preferred.

265. EXPERIMENT 12-F. — Operating Motors on a Symmetrical Three-Wire System. — Provide a three-wire source of supply, as in Fig. 206 or in Fig. 207, and connect to it an ordinary shunt motor as in Fig. 223. (*a*) Load the motor to its rated capacity at the lowest speed possible, viz., strongest field and half voltage on the armature. Gradually increase the speed by weakening the field as far as sparking will allow; vary the torque accordingly, so as to keep the same horse-

power output. Read armature and field amperes, volts, brake load and speed, as in a regular brake test.

(*b*) Having reached the speed limit, switch the armature over to the full voltage; start again with the strongest field and continue the test as before, keeping horse-power output constant. After each reading, release the brake before going to the next point; read input and speed at no load, so as to see per cent speed variation between no load and full load.

Report. Plot to speed as abscissæ all the data observed, also an efficiency curve.

266. EXPERIMENT 12-G. — Operating Motors on an Unsymmetrical Three-Wire System. — An unsymmetrical three-wire system is produced, as explained in § 245. The experiment is performed in a way similar to the preceding one. The armature is connected in succession across the three different voltages.

TROUBLES IN DIRECT-CURRENT MACHINES.

267. Troubles in an electrical machine may be either of mechanical or of electrical nature. Mechanical troubles, such as unbalancing, defective bearings, etc., can be comparatively easily detected; they are remedied in the same way as in any non-electrical machine. Purely electrical troubles require more special knowledge for their detection; some of the symptoms, and the detection of the more important electrical troubles, are described below.

The three parts of a direct-current machine that may give trouble of an electrical nature, are: armature, commutator, and field magnets; these will be considered separately. It is hardly possible to give detailed and complete instructions for locating troubles, since they often occur in a manner and place in which they are least expected. Sound judgment, and the instinct bred of experience, permit a trained man to locate the trouble in a few minutes, where a beginner may spend days.

268. Troubles in Field. — The principal troubles in the field circuit are: The winding may be partly or totally short-circuited, or grounded on to the frame; it may be connected in a wrong way so as to produce two adjacent poles of the same polarity; the winding may be broken (open circuit); the machine may have lost its residual magnetism, or may have it in the wrong direction. All these troubles can be detected by comparatively simple means. A short-circuit is detected by measuring the resistance of the winding with a Wheatstone bridge, or by

the drop-of-potential method. If the winding is grounded to the frame, a lamp will light up between the winding and the frame; or else the ground can be detected by a Wheatstone bridge, a galvanoscope, a magneto, etc. If the ground resistance is high, it is measured with a voltmeter, as explained in § 481. One ground connection is not so bad, as long as the rest of the circuit is thoroughly insulated from the ground. But should another point touch the ground a short-circuit is produced, with all its harmful effects. An open circuit, or a loose connection, is also easily traced out by a lamp. Wrong polarity can be detected by bringing a magnetic needle near the poles. Loss of residual magnetism is usually manifested by the generator failing to excite itself, though of course a broken or a wrong connection has the same effect.

With a sufficient knowledge of the theory and performance of direct-current machines, the possible causes of a trouble may be investigated and gradually eliminated, until the actual cause is found.

269. Troubles in Armature. — There are three principal faults in the armature to be looked after: short-circuit, open circuit, and grounded winding. The usual method for locating a short-circuit consists in putting a current through the armature and measuring the voltage drop between each two adjacent commutator segments by means of a milli-voltmeter, or a low-reading voltmeter, as shown in Fig. 225. At the place of a short-circuit, as between *a* and *b*, the drop is almost zero, or at any rate much lower than between other segments. When the trouble is thus located, it remains to determine whether the short-circuit is in the winding *c* itself or between the two commutator bars. This is done by disconnecting the suspicious coil from the commutator and trying the voltage drop again between the same two commutator bars and between the ends of the coil.

A modification of this test consists in using alternating current, instead of a direct current, and applying a telephone receiver instead of a milli-voltmeter. Where the winding and the commutator are clear of short-circuit, a distinct humming is heard in the receiver; the humming ceases when passing over the short-circuited bars. An open circuit is also tested by means of a low-reading voltmeter. It will be easily seen that in this case the deflection suddenly rises when passing over the fault. A ground is detected by the same means as in the field (§ 268).

270. Commutator Troubles. — These are usually manifested in an excessive heating and sparking; sometimes the cause lies in the commutator itself, and sometimes in the armature winding, as explained above. The principal commutator troubles proper are: rough surface,

a high bar, a wrong setting of the brushes, and a short-circuit between the bars. A rough surface, or a high bar, is usually detected by an inspection of the commutator as soon as the trouble has been noticed. The improper setting of the brushes is discovered by shifting the brushes until the position of minimum sparking is found. Old machines usually require shifting of the brushes with various loads because of a large armature reaction. More modern machines generally have a permanent setting from no load to full load.

A short-circuit between the bars is the most serious trouble and requires immediate attention; if the bars *a* and *b* (Fig. 225) are short-

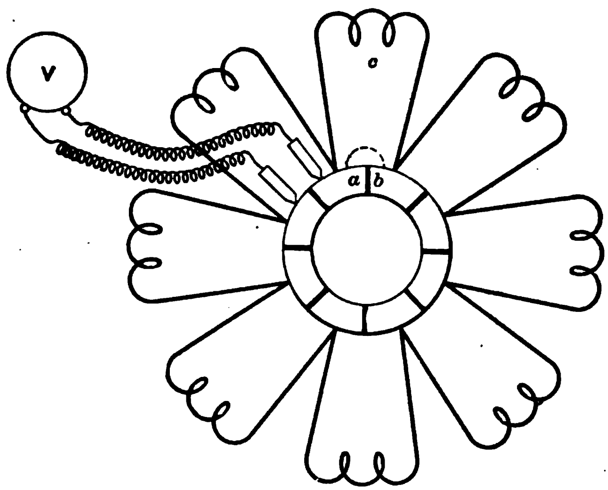

FIG. 225. Locating faults in an armature, using a voltmeter.

circuited they short-circuit the coil *c*. As this coil revolves in a strong magnetic field, heavy currents are produced in it, and the coil is usually burned out in a short time. The method for locating this trouble is the same as for locating a short-circuited coil in the armature and is described in the previous article.

271. EXPERIMENT 12-H. — Locating Troubles in a Direct-Current Machine. — The best way to arrange this exercise would be for the instructor to provide several faults in a machine and then let the student locate and remedy them. The objection to this method is, however, that an inexperienced man may spend hours and even days before he finds a trouble. Therefore it is deemed advisable to let the student himself provide various faults in the machine, observe its behavior, and then perform the measurements described above for

locating troubles. In this way more can be accomplished in a shorter time, and various faults studied systematically. Various troubles give different symptoms according to whether the machine is running as a generator or a motor; it is, therefore, desired that the student should run the machine both ways, whenever practicable.

(a) Begin the experiment by short-circuiting part of the field winding and operate the machine as a generator and as a motor; note the abnormal symptoms observed. Then do the same with the other troubles enumerated in § 268: make wrong connections, produce an opposite residual magnetism, etc. Report all the symptoms observed, and state how you would locate the true cause, by gradually eliminating all other possible causes.

(b) Produce in the armature the faults described in § 269 and observe the symptoms accompanying the faults. Care should be taken not to damage the machine, as these faults are usually accompanied by vicious sparking and heavy currents. The necks of two commutator bars may be provided with small screws for placing an artificial short-circuit between them. Use a small fuse wire for short-circuiting, so that it would blow out before the coil could be damaged.

It is interesting to observe the effect of two or more coils being short-circuited simultaneously; figure out how the coils can be located in this case by the drop-of-potential method.

(c) After having had sufficient practice with the above faults, the student should feel enough confidence in himself to locate some prearranged troubles, without knowing their place or nature. One man of the section, or the instructor, may be asked to arrange one or more faults in the machine, for the others to locate. This will bring more interest into the work and will make it more profitable.

CHAPTER XIII.

DIRECT-CURRENT MACHINERY — EFFICIENCY AND LOSSES.

272. A DIRECT-CURRENT machine can be operated either as a generator or as a motor. In the former case it transforms the mechanical energy of the prime mover into electrical energy available at its terminals; in the second case it converts the electrical input from the line into mechanical energy available on its shaft. In both cases this transformation of energy is necessarily accompanied by losses in the machine itself.

These losses cause the output of the machine to be less than the input; the ratio of the two is called the efficiency of the machine. Efficiency is thus indirectly a measure of the losses. By definition

$$\text{efficiency} = \frac{\text{output}}{\text{input}} \quad \ldots\ldots\ldots \quad (1)$$

This expression holds true for either a generator or a motor. Efficiency may also be expressed in terms of output and losses thus:

$$\text{Efficiency of generator} = \frac{\text{electrical output}}{\text{electrical output} + \text{losses}}; \quad \ldots \quad (2)$$

$$\text{Efficiency of motor} = \frac{\text{mechanical output}}{\text{mechanical output} + \text{losses}}. \quad \ldots \quad (3)$$

The efficiency of a motor may also be conveniently expressed in the following form:

$$\text{Efficiency of motor} = \frac{\text{Electrical input} - \text{losses}}{\text{Electrical input}} \quad \ldots\ldots \quad (4)$$

273. Direct and Indirect Methods for Determining Efficiency.— The four above expressions for efficiency are identical in principle, the efficiency in all of them being expressed by the ratio of output to input. Two experimental methods may be used for determining efficiency, according to whether it is expressed explicitly in terms of both input and output, as in the formula (1), or of only one of these and the losses,

as in (2), (3) and (4). The first method is sometimes called *the direct method* for determining efficiency, the second one — *the indirect*. Both are used in practice, and there are cases in which each one is preferable.

When both input and output are to be measured directly, an actual load test is necessary: a brake is used with motors, generators are generally loaded on resistances. While the measurement of the *electrical* input or output is comparatively simple, determining the *mechanical* power requires a brake, a transmission dynamometer, or similar devices which are neither easily operated nor accurate in results, even on small machines, and hardly applicable for large machines. Moreover, the waste of power unavoidable with such tests is objectionable, and in many cases even prohibitive, because it may be quite impossible to get the necessary amount of power.

At any rate, the direct method gives only the sum total of the losses and not the separate losses. The results obtained cannot be very accurate, because the losses are determined as a difference between two large and not very different quantities — the input and the output. A small error in either of these may result in a considerable error in the value of the losses.

The *indirect* method is therefore usually employed, and by its use the segregation of the losses into the separate components is made possible. The procedure is, in brief, to run the machine under test at *no load*, and to determine the power necessary for driving it. The power is used in this case entirely for overcoming the losses, and is thus a direct measure of the sum total of the losses.

274. Losses in Direct-Current Machines. — The losses in an electric machine, whether running as a motor or as a generator, can be subdivided into three different classes:

(a) *Copper loss* (I^2R) in the armature, and in the field circuit;

(b) *Iron loss* (hysteresis and eddy currents) in the armature core;

(c) *Mechanical losses:* bearing friction, brush friction, and windage (air resistance).

The copper losses need not be determined experimentally; it is only necessary to measure the ohmic resistances of the corresponding windings; then the I^2R loss can be calculated for any desired value of the current.

The iron loss in any machine depends upon the magnetic flux of the machine and upon its speed. In shunt-wound machines the flux is constant as long as the field current is constant. The speed is also approximately the same at all loads; therefore the iron loss under these conditions is approximately constant.

The brush friction and the windage loss depend on speed only. The bearing friction is constant in a direct-connected motor, but when the motor is used for belt drive the friction depends on the tension of the belt. This increase in friction could hardly be taken into account, and it is customary not to charge it to the motor.

Thus the items (b) and (c), viz., iron loss and friction in a shunt-wound machine, can be assumed nearly constant at all loads, and having the same value as at no load. This gives a convenient method for measuring these losses; all that is necessary is to measure the amount of power put into the armature of the machine, running as a motor, at no load. This input is all converted into iron loss and friction, with the exception of a small part of it, which is necessary for supplying the I^2R loss in the armature winding and the brushes. The correction is usually negligible, but, if necessary, can be readily calculated.

There are cases where the machine under test cannot be run as a motor; for instance, if it is a 500-volt machine, and only a 110-volt source of supply is available. In such cases, the machine is belted to a small auxiliary motor and driven at the right speed and excitation, at no load. The input into the driving motor is equal to the losses in the machine, with a correction for the losses in the motor itself.

To determine the losses in the driving motor the belt is taken off, and the motor run at no load within the same limits of speed and excitation as when driving the machine under test. The input into its armature is a measure of the losses in the motor itself, and can thus be calculated and eliminated from the results.

Thus, there are two methods for determining the losses in a machine. The machine under test may be driven electrically as motor, or mechanically by an auxiliary motor. A third possible way, the so-called retardation method, is described in §§ 283 to 287.

275. Example of Calculating Efficiency from Losses. — Suppose that it is required to calculate the efficiency curve of a 50 horse-power 220-volt motor. It was found that at no load the motor takes 10.6 amperes (armature current), and the field current at which the motor is supposed to run is equal to 5.8 amperes. The resistance of the armature was found by measurement to be 0.0377 ohm. We have: no-load losses (neglecting copper loss) consisting of iron loss and friction $= 220 \times 10.6 = 2.33$ kilowatts; excitation loss $= 220 \times 5.8 = 1.275$ kilowatts; total losses independent of the load $= 2.33 + 1.275 = 3.605$ kilowatts. The copper loss in the armature depends upon the load; as we do not know what current the motor would take at an output of 50 horse-power, we have to find it by trials. A still better method is to construct the whole efficiency curve from no load to one and a quarter

load and then take from this curve the point corresponding to full load.

An ideal 50 horse-power motor takes at full load,

$$\frac{50 \times 746}{220} = 170 \text{ amp.};$$

the real motor will probably take 190 or 200 amperes. Therefore, we construct the efficiency curve for points between, say, 100 amperes and 250 amperes; then we can be sure that the full-load point lies on this curve. Take, for instance, the 150-ampere point. Total electrical input $= (150 + 5.8) \times 220 = 34.28$ kilowatts; copper loss in the armature $= 150^2 \times 0.0377 = 0.848$ kilowatts; total loss $= 3.605 + 0.848 = 4.453$ kilowatts.

$$\text{The efficiency is } \frac{34.28 - 4.453}{34.28} = 87 \text{ per cent.}$$

$$\text{The output} = \frac{34.28 - 4.453}{0.746} = 40.1 \text{ horse-power.}$$

In this way, efficiency can be calculated for various values of output; and the efficiency corresponding to an output of 50 horse-power found from the curve plotted.

This method of figuring efficiency from losses is not quite correct, for the reason that the speed does not remain altogether constant at all loads, but may drop a few per cent between no load and full load. In order to take this into account, the no-load run is sometimes supplemented by the so-called *ampere-speed curve* giving actual values of speed of the motor, with varying input. The no-load test is then run within the limits of the speeds of the motor, and in figuring out the efficiency, the values of the iron loss and friction are taken for the speed corresponding to a given amperes input.

When the machine under test is driven mechanically, the losses in the driving motor are taken into account as follows: Suppose, for instance, that in one of the runs the input into the armature of the auxiliary motor was 5 amperes at 104 volts, or 520 watts. When the auxiliary motor was run alone (with the belt off) it took 1.3 amperes at 101 volts, with the same excitation and the same speed in both cases. The resistance of the motor armature was found by measurement to be $= 0.16$ ohm. Then the iron loss and friction in the motor amount to $131.3 - 1.3^2 \times 0.16 = 131$ watts; the iron loss and friction in the machine under test is therefore

$$520 - 131 - 5^2 \times 0.16 = 385 \text{ watts.}$$

It will be seen from these figures that the correction for I^2R is small and in many cases may be neglected altogether.

276. EXPERIMENT 13-A. — Efficiency from Losses, Machine Driven Electrically. — (a) Connect up the machine under test, as in Fig. 212, and run it at no load and at the rated voltage.* Vary the speed within the range for which the values of efficiency are desired, by regulating the field current. (b) Determine the resistance of the armature by the drop-of-potential method (§ 10). (c) If the machine under test is intended to be used as a motor, and accurate results are required, ampere-speed curves should be taken. For these, the machine is belted to a generator or a blower and is driven at the values of the field current and armature current for which the efficiency is desired. The no-load

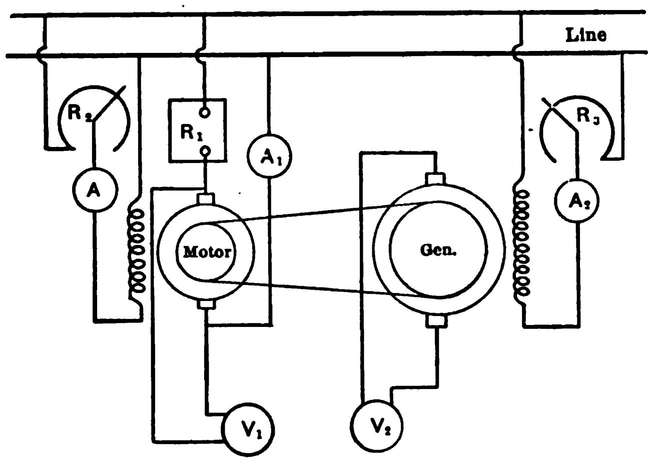

FIG. 226. Separation of losses in a direct-current machine. The machine is driven mechanically as a generator.

runs are repeated for the same values of field current and speed; speed is regulated in this case by the rheostat in the armature circuit.

If the machine under test is intended to be used as a generator, no ampere-speed curves are necessary, but an excitation characteristic should be taken instead (see § 227), so that the values of the field current at different loads, but with a constant terminal voltage, may be known. Then the no-load runs are taken for the corresponding values of field current and speed, the latter being again varied by a rheostat in the armature circuit.

Report. Plot ampere-speed curves and an excitation characteristic;

* Before beginning the test it is advisable to let the motor run idle for at least half an hour, in order to get the bearings warmed up and the friction more constant. This may not be practicable in the laboratory, because of the limited amount of time for test, but this precaution is advisable in more accurate work.

also curves of no-load losses. Figure out the resistance of the armature. Plot to horse-power output as abscissæ, efficiency curves of the machine working as a motor, with two or three different values of the exciting current. Plot to kilowatt output as abscissæ an efficiency curve of the machine working as a generator.

277. EXPERIMENT 13-B. — Efficiency from Losses, Machine Driven Mechanically. — The experiment is performed as explained at the end of § 275. The diagram of connections is shown in Fig. 226; the

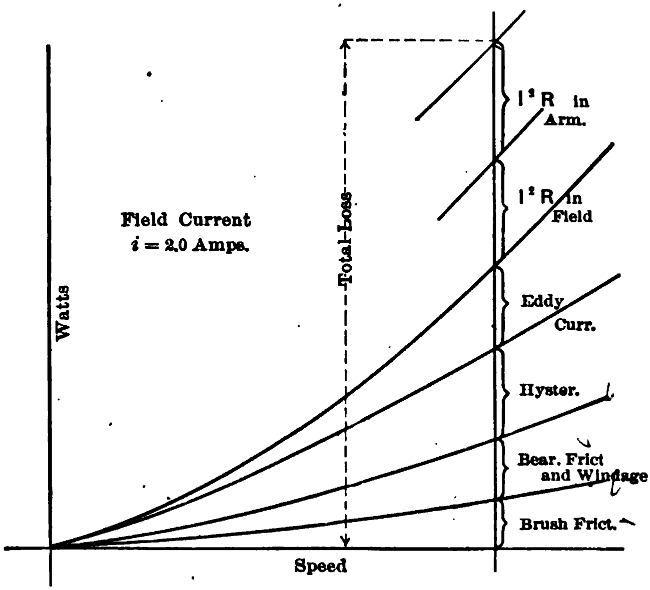

FIG. 227. Separate losses in a direct-current machine.

driving motor is at the left, the machine under test at the right. The fields of both machines are excited separately, so that the power loss in the field windings does not enter into calculations.

This method is usually selected when no source of power is available to drive the machine electrically, as in the preceding experiment; therefore, taking an ampere-speed curve is out of the question, and in figuring out the efficiency of the motor, speed variations with load can only be estimated. If the machine is intended to be used as a generator, it is possible to take its excitation characteristics, provided a driving motor of sufficient size (of a capacity about 10 per cent of that of the generator) is available.

Before leaving the laboratory, measure the resistance of the armature. Report requirements are similar to those for the preceding experiment.

278. Separation of Losses. — The designer of electrical machinery — and often the user — is not satisfied to know the sum total of the losses, but desires to know the separate component losses, as shown in Fig. 227. The same losses are shown in the following table.

Total loss	(1) Copper loss	Copper loss in armature; Copper loss in field.
	(2) Core loss	Hysteresis loss; Eddy current loss.
	(3) Mechanical losses	Bearing friction; Brush friction; Windage.

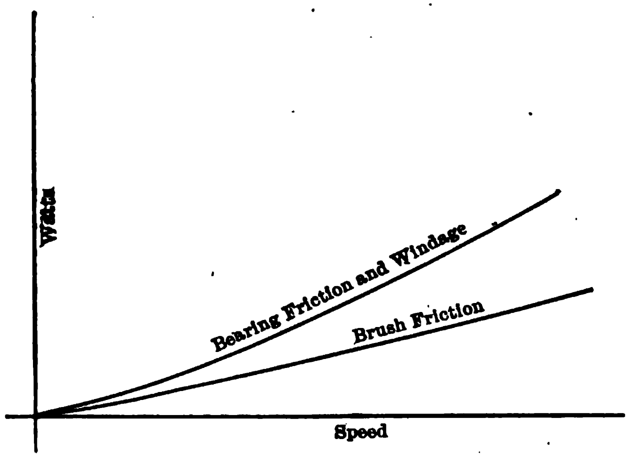

FIG. 228. Brush friction separated from bearing friction and windage.

Knowledge of the separate losses is of importance for the following reasons:

(a) The losses and their dependency on the load, speed, etc., determine the rating of the machine for different classes of service (intermittent load, variable load, constant load, etc.).

(b) The magnitude of the separate losses is a check on the quality of materials, workmanship, and design.

(c) Knowing the values of the principal losses the designer is enabled to vary the dimensions of the machine, still keeping its efficiency as high as competition may require, and preserving reasonable limits of temperature rise.

Of the three kinds of losses, only those mentioned under (2) and (3) need to be discussed here. Copper loss, I^2R, is easily calculated from the measured resistances of the windings.

279. Core Loss and Mechanical Losses. — Frictional losses (3)

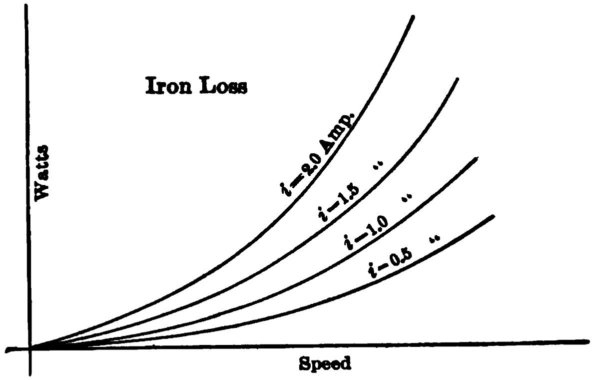

FIG. 229. Curves of iron loss as a function of speed and of exciting current.

depend only on the speed of the machine, and may be plotted as in Fig. 228. In ordinary practical testing, bearing friction is never separated from windage, and the author is not aware of any simple method

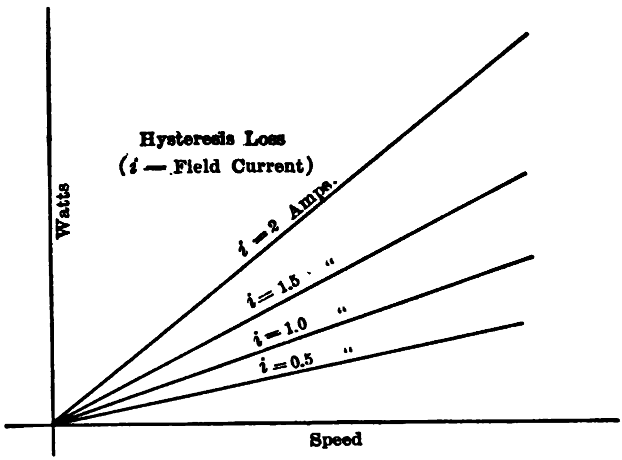

FIG. 230. Curves of hysteresis loss as a function of speed and of exciting current.

for doing this. One method, that suggests itself, would be to have the bearings themselves pivoted so as to measure the friction torque by means of a sensitive balance. Another method would be to run the machine in vacuum, thus eliminating the windage.

Core loss depends on speed and on field current, and is usually represented by a set of curves, as shown in Fig. 229. The components of the core loss — hysteresis and eddy currents — are shown in Figs. 230 and 231. It is important for the manufacturer to have eddy currents separated from the hysteresis loss. A high hysteresis loss means that the iron used was of an inferior quality, or the flux density allowed was too high; high eddy-current loss indicates that the laminations are too thick, or not sufficiently insulated from each other. Thus the remedy is quite different in the two cases.

The sum of losses (2) and (3), or, as it is sometimes called, total no-

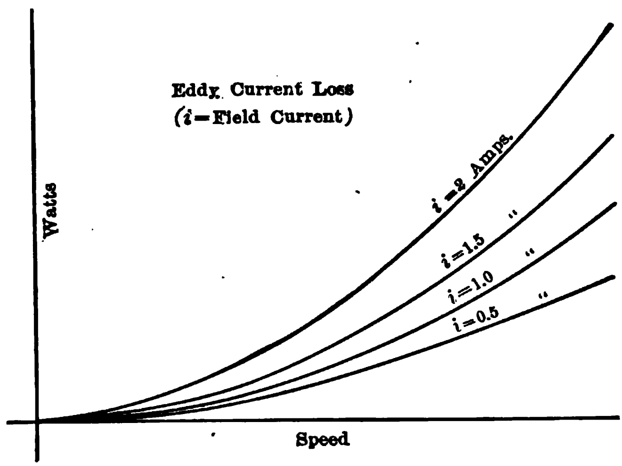

FIG. 231. Curves of eddy-current loss as a function of speed and of exciting current.

load loss (Fig. 232), is determined by measuring the power necessary for driving the machine at no load. The machine may be driven (1) *electrically* as a motor, (2) *mechanically* as a generator (from an auxiliary motor), (3) the kinetic energy of the machine itself is utilized (*retardation method*). All these methods are used according to the local conditions, and all are applicable for separating the losses in either series, shunt- or compound-wound generators and motors.* With some changes the same methods can be used for alternating-current machines. The details of these three methods are given below.

The separation of iron loss into its components (Figs. 230 and 231)

* A special method for separating iron loss from friction in a series motor is described in § 292.

is done by calculation, on the basis of the fact that hysteresis and eddy currents vary in a different way with changes in speed and field current (§ 288).

280. EXPERIMENT 13-C. — Separation of Losses, Machine Driven Electrically. — The purpose of the experiment is to separate the total losses in a direct-current generator or motor into the components shown in Fig. 227. The machine under test is connected up as shown in Fig. 212 and driven electrically, as a motor, within as wide limits of field current and speed as is feasible. The machine ought first to be run for at least half an hour at a high speed in order to attain

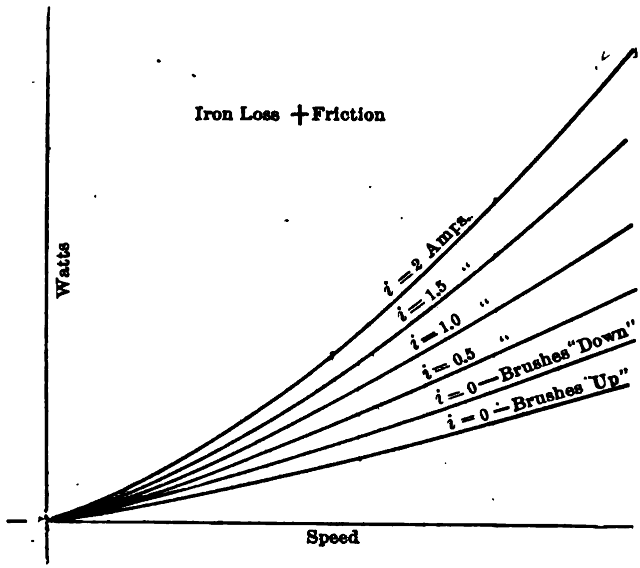

FIG. 232. Total no-load losses as a function of speed and of exciting current.

constant friction conditions. Lubrication must, of course, be maintained the same during the whole test.

(*a*) Begin the test with the strongest field current possible and at maximum speed that can be obtained with this field current, — i.e. at full voltage. If necessary, the pressure at the armature terminals can be raised even above the rated voltage of the machine. Read armature volts and amperes, field amperes and speed. Then, *keeping field current constant at this maximum value*, gradually reduce the speed by 6 or 8 approximately equal steps to its lowest possible limit, by introducing resistance into the armature circuit. The readings (with a small correction for the armature I^2R) will give directly the data for the upper curve in Fig. 232.

(*b*) Repeat similar runs with smaller values of the field current corresponding to the other curves on the same sheet.

The two lower curves cannot in this case be determined directly from the test, since the machine requires some appreciable field current in order to run as a motor. The friction can be determined by calculation, as is shown in the next article. Also, the separation of the brush friction from the bearing friction and windage cannot be done in this case as accurately as when the machine is driven mechanically from an auxiliary motor. This is because at least two of the brushes must lie on the commutator when the machine drives itself as a motor. The only possible way is to lift up *part* of the brushes and from the decrease in input to figure out what would be the reduction in power if *all* the brushes could be removed; this reduction may be assumed to be due to brush friction. It is advisable to perform this test with a low field current, since in this case the friction constitutes a larger percentage of total losses.

(*c*) Measure the resistances of the windings.

(*d*) If necessary, take an ampere-speed curve, or an excitation characteristic (see § 276).

Report. Plot curves shown in Fig. 232. Separate friction from iron loss as is explained in § 281; separate hysteresis loss from eddy currents, as shown in Fig. 236. Do this at least for the normal excitation of the machine, though preferably for all the curves shown in Fig. 229, so as to show the influence of the field current on the value of iron losses. Plot all the losses at the normal field current of the machine to speed as abscissæ (Fig. 227); figure out the efficiency at full load and at the rated speed for the machine running as generator and as motor.

281. Separation of Friction from Iron Loss by Calculation. — It is mentioned in the previous article that when the curves shown in Fig. 232 are obtained by driving the machine electrically as a motor, it is impossible to obtain friction alone from test. This is due to the fact that the machine must have some field excitation to run as a motor, so that some iron loss is necessarily present; the friction curve in this case is determined by calculation. This is done by applying the self-evident principle that *the friction loss is the limit towards which the total loss is tending* when the excitation is being reduced to zero, the speed being kept constant. In order to make use of this principle, the curves of total loss in Fig. 232 are replotted, as shown in Fig. 233, to volts at the armature terminals as abscissæ, each curve referring to a certain constant speed. With the machine running at no load, volts at the armature terminals are practically equal to the counter-e.m.f. of the machine (§ 251). These curves are then produced to the axis of ordi-

nates as shown by dotted lines; the intercepts give the values of friction for the corresponding speed. Plotting these values of friction against speed as abscissæ (Fig. 232) the required friction curve is obtained.

This method becomes clear upon consideration of the evident fact that the machine being under motion, the armature volts (counter-e.m.f.) can become zero only when the field has a zero value. With zero field there can of course be no iron loss, and the whole loss consists of friction alone.

The dotted parts of the curves in Fig. 233 are produced either empir-

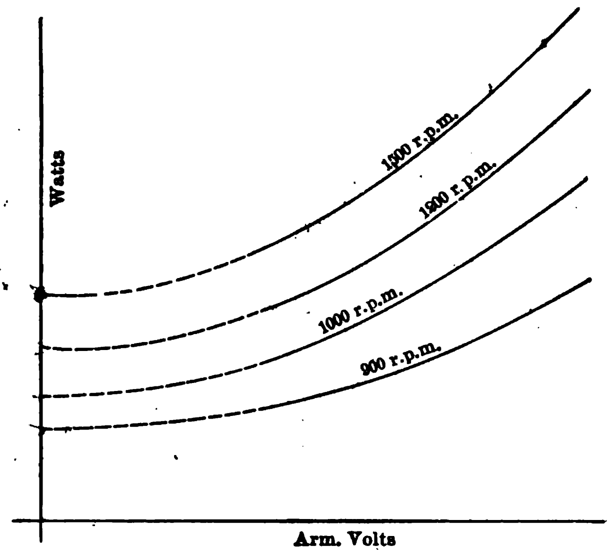

FIG. 233. Extrapolation of the total-loss curves in order to separate friction from the iron loss.

ically, or theoretically, since they are practically parts of parabolæ. The general equation of the curves is

$$W = F + kE^2, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where W is total loss, F is the friction loss, and E — the voltage at the armature terminals; k is a constant the numerical value of which does not enter into the calculations. This equation is deduced as follows: Each curve refers to a particular speed; therefore the friction loss is constant for each curve. The hysteresis loss increases somewhat slower than the square of the flux (Steinmetz's $B^{1.6}$); eddy-current loss increases as the square of the flux. With a constant speed the flux is propor-

tional to the voltage; thus the iron loss can be assumed as approximately proportional to E^2. Thus the above equation becomes obvious. Writing it for two points on the curve, we have

$$W_1 = F + k E_1^2$$
$$W_2 = F + k E_2^2$$

whence

$$F = \frac{W_1 - W_2 \left(\frac{E_1}{E_2}\right)^2}{1 - \left(\frac{E_1}{E_2}\right)^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

This value of F gives the point at which the curve meets the axis of ordinates.

282. EXPERIMENT 13-D. — Separation of Losses, Machine Driven Mechanically. — The purpose of the experiment is to separate the total losses in a direct-current generator or motor into the components shown in Fig. 227. The machine under test is belted or direct-connected to an auxiliary motor and driven at no load, at various speeds, with varying field excitation. The scheme of connections is shown in Fig. 226; both machines should be separately excited in order not to introduce into the calculations the power lost in the fields. The input IE into the armature of the driving motor represents the sum of iron loss and friction in both machines, less a small correction for I^2R loss in the motor armature itself.

(*a*) The machines should first be run for at least 30 minutes at a high speed in order to warm up the bearings and produce a constant friction. Then the machine under test is excited to its highest possible value, and the speed raised to its highest safe limit. Read all the instruments, as shown in Fig. 226, and also the speed of the set. Then gradually reduce the speed, either by increasing the motor field current or by putting some resistance into its armature circuit;* both methods can be used simultaneously if preferred. The field current of the machine under test must be kept constant during each run, the same readings being taken for several speeds. This test corresponds to the upper curve in Fig. 232, except that the losses in the driving motor must first be subtracted from the volt-ampere input into its armature, as is explained at the end of § 275.

(*b*) The same run should be repeated with lower values of the field current in the machine under test, until a sufficient number of curves

* This latter method is preferred by many, since it is simpler to correct data for the variable losses in the driving motor if its field has been maintained constant.

is obtained (five or six). The last curve is that with the field circuit opened and corresponds to the frictional loss alone.

(*c*) After this, the brushes should be lifted from the commutator, so as to eliminate their friction; the difference in the input with the brushes " down " and " up " gives the value of the brush friction. If the machine has several pairs of brushes it is advisable to lift them up in pairs, to check the fact that the friction is reduced in proportion to the number of brushes removed.

(*d*) Finally the belt should be taken off and the driving motor run

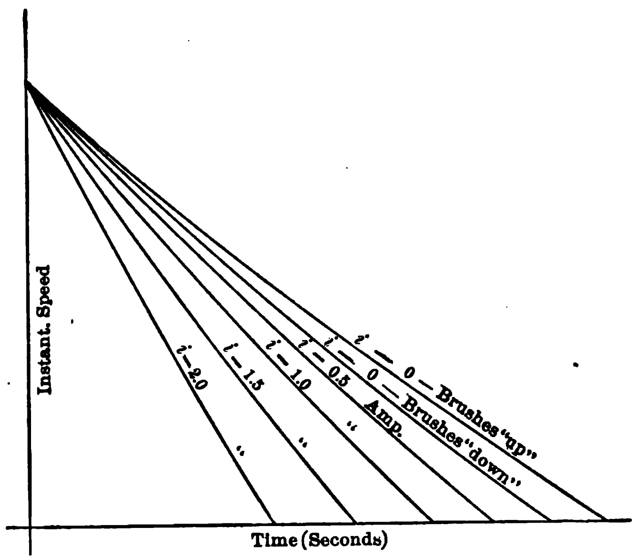

FIG. 234. Retardation or time-speed curves for various values of the field current.

alone at the same speeds and with the same values of exciting current as before, in order to determine its own losses. The loss in the belt can be only roughly estimated. The arrangement must be such as to make this loss as small as possible. Under normal conditions it may be assumed to be equal to 2 per cent of the power transmitted.

(*e*) Measure armature resistances of both machines, and if necessary take ampere-speed curves, or an excitation characteristic (see Exp. 13-A, § 276).

Report. The requirements are the same as in § 280, except that the iron loss is separated from the total loss directly, by using the experimentally determined friction curve.

RETARDATION METHOD.

283. Instead of driving a machine electrically or mechanically for separating the losses, it may be brought up to the highest safe speed and the power shut off; the machine then gradually slows down to a standstill, overcoming the losses by its stored kinetic energy. While it is slowing down, instantaneous values of speed are read every few seconds. Such runs are made with various values of field current, and the results plotted as speed-time or *retardation* curves (Fig. 234).

The form of these curves depends on the relative magnitude of iron loss and the friction, and on their variation with speed. A method is given in § 285 for converting these curves, by calculation, into those shown in Fig. 232; subsequently the losses can be separated, as already explained.

This method is more applicable to large machines, in which the stored energy of the armature is sufficient to maintain the rotation during a comparatively long time (several minutes), so that instantaneous speeds can be taken with considerable accuracy. If the machine has been brought up to speed mechanically, by an auxiliary motor, the belt is thrown off; if it was speeded up electrically, the armature circuit is broken.

284. Measuring Instantaneous Speeds. — The principal difficulty in performing a retardation test lies in the accurate measurement of speed; otherwise the method is simple and reliable, especially with large machines. Several methods are used for measuring instantaneous speeds:

(1) A small magneto, belted to the machine and connected to a sensitive voltmeter, is probably the best device for the purpose unless a special recording tachometer is available.

(2) An ordinary speed-counter may also be used to record total number of revolutions from the moment at which the connection to the external power was broken. This speed-counter is read every two or three seconds without stopping it; the difference of each two consecutive readings gives the total number of revolutions during these two or three seconds. From these the average speed corresponding to the middle of this time period can be determined.

(3) Still another method is to leave the voltmeter across the armature terminals, and to read volts every two or three seconds. If the field current is kept absolutely constant, the volts are exactly proportional to the speed. Before breaking the connections to the source of external power, the coefficient between the speed and the voltage must be determined, so as to be able to convert the observed time-voltage

curve into a time-speed curve. This method is not quite convenient for the run with the fields opened, unless a low-reading voltmeter is used, the speed being measured by the voltage induced by the residual magnetism. If this is not practicable, one of the two other above-mentioned methods for measuring speed can be used for this run.

(4) It is important to measure accurately the speed during the first part of the retardation curves, just after the power is shut off, because the values of the losses are usually desired at these speeds. Sumpner's differential voltmeter method is convenient for the purpose. The machine is speeded up as a motor, and the armature circuit is opened on one side of the line only, by a single-pole switch. A low-scale direct-

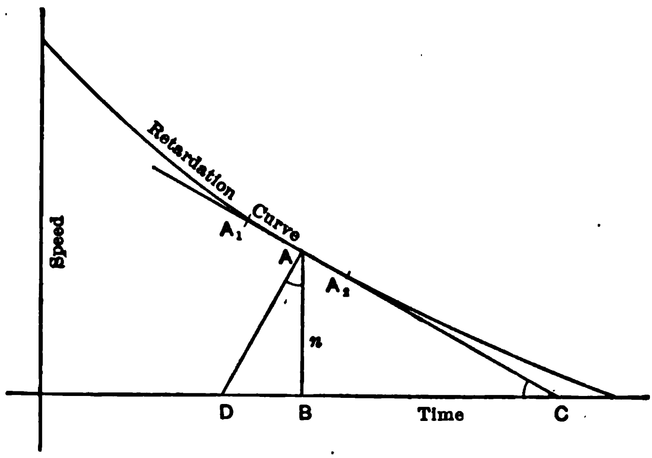

FIG. 235. Analysis of a retardation curve.

current voltmeter is connected across the switch terminals and shows practically zero, as long as the switch is closed. When the switch is opened and the motor slows down, the voltmeter measures the difference between the line voltage and the e.m.f. induced in the motor.

The line voltage being constant, and the induced e.m.f. proportional to instantaneous speeds, voltmeter readings are proportional to the drop in speed. When the end of the scale is reached, the switch is closed, and the motor speeded up again for the next retardation run.

285. Theory of the Retardation Method. — The energy stored in the armature at a certain speed, $n = BA$ (Fig. 235), is $\frac{1}{2} Ga^2$, where G is the moment of inertia of the revolving part, and a is its angular velocity. The latter is proportional to the speed n expressed in r.p.m., so that the stored energy can be also represented in the form $\frac{1}{2} Cn^2$, where C is a

certain constant proportional to the moment of inertia of the revolving part.

If W is the value of the total losses (iron loss and friction) corresponding to this speed, we have the relation

$$-d\left(\frac{Cn^2}{2}\right) = W.\,dt. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

which expresses, that the decrease in kinetic energy during an infinitesimal interval of time dt is equal to the work performed by the armature in overcoming the losses W during the same interval. Differentiating, we obtain:

$$-Cndn = W.\,dt$$

or

$$W = -C.\frac{ndn}{dt} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

It is shown below that ndn/dt is numerically equal to the length of the *subnormal* BD (Fig. 235) to the curve showing the relation of n to t, which is the retardation curve for the machine tested. Thus we obtain the relation:

$$W = C.\,BD \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

or, *instantaneous total loss W is proportional to the length of the subnormal to the retardation curve.*

Proof that $-ndn/dt = BD$. The ratio $-dn/dt$ is the trigonometrical tangent of the angle ACB, the line AC being tangent to the retardation curve at the point A. If AD is normal to the curve, the angle DAB is equal to the angle ACB. From the triangle DAB we have

$$DB = AB \,.\, \tan DAB = -n.\,\frac{dn}{dt}$$

which proves the above proposition. The sign "minus" is necessary because dn is negative (speed decreases with time), while DB is positive.

The shape of the revolving part of an electric machine is too complicated to allow its moment of inertia G to be calculated with sufficient accuracy; therefore G, or the constant C which is proportional to it, is eliminated by performing an additional experiment, as is explained in the next article.

Thus curves shown in Fig. 234 are reduced to those in Fig. 232 by drawing normals and measuring the corresponding subnormals, which, to a certain scale, represent iron loss + friction. Some error is introduced by the uncertainty of the exact direction of the normal, but with reasonable care, reliable results are obtained. The simplest way

of drawing normals is to take two points, A_1 and A_2 (Fig. 235), at small equal distances from A and to draw AD perpendicular to A_1A_2. Some prefer the analytical method of calculating W to that of drawing tangents and normals. Writing the equation (7) for the finite period of time between the points A_1 and A_2, we get

$$\tfrac{1}{2} C (n_1^2 - n_2^2) = W (t_2 - t_1) \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

From this equation W is calculated and is assumed to represent the losses at the point A, for the moment of time $\tfrac{1}{2} (t_1 + t_2)$.

After the retardation curves shown in Fig. 234 have been reduced to those in Fig. 232, the separation of hysteresis from eddy currents is done as in §§ 288 to 290.

286. Elimination of Moment of Inertia of Revolving Part. — The constant C, which enters into the preceding formulæ, and which is proportional to the moment of inertia of the revolving part of the machine, may be eliminated by two methods:

(1) The value of the loss W is determined for one point, by an independent method;

(2) The amount of loss W is changed by a known amount.

According to the first method the machine under test is driven electrically or mechanically at a certain speed n, and with a certain field current, the value of total loss W being determined from the amount of power input into the armature. Then the subnormal DB is measured at a point corresponding to the same speed n and the same field excitation. This gives directly the scale for W, since $W = C \times BD$. If, for instance, W was determined to be 600 watts, and $DB = 2.5$ cm., the scale is $600 \div 2.5$, or 240 watts loss per 1 cm. length of subnormal.

According to the second method, an extra retardation run is taken with a known additional load w put on the machine. Then we have

$$\left.\begin{aligned} W &= C \,.\, BD \\ W + w &= C \,.\, B_1D_1 \end{aligned}\right\}$$

where B_1D_1 is the subnormal to the new retardation curve. Eliminating W, we get:

$$C = \frac{w}{B_1D_1 - BD} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

The load w may be obtained, either by closing the armature on a resistance and keeping the output constant with a wattmeter; or by applying a Prony brake with a definite torque. With either method w can be kept constant through a limited range of speed only. This is sufficient, however, as only one point on the curve is necessary. Sumpner's differential method for measuring speed (§ 284) is quite convenient for the purpose. See Note on page 324.

287. EXPERIMENT 13-E. — Separation of Losses by the Retardation Method. — (*a*) Have the machine wired so as to be able to bring it up to speed either electrically or mechanically; run the machine for about thirty minutes, to attain steady conditions of lubrication. Bring it up to the highest safe speed, measure this speed, and then suddenly open the circuit (both armature and field), allowing the machine to slow down to a standstill. Measure instantaneous retardation speeds by one of the methods described in § 284. Repeat the run several times until you have learned to read speeds quickly; a metronome is of assistance in this work.

(*b*) Bring the machine up to speed again, and simultaneously with opening the circuit lift up the brushes, taking a retardation curve without brush friction. Repeat this run several times until you get reliable results.

The armature circuit can be most conveniently opened by a circuit-breaker; in breaking the field circuit special precautions must be taken in view of the high inductance of the field windings. It is well to provide a special *field-discharge* switch, which in opening the main circuit closes the field winding upon itself, through a suitable resistance. In this way an easy path is offered for the inductive kick, and the danger of breaking down the insulation is minimized.

(*c*) After this, make several retardation runs, leaving the field circuit closed and opening only the armature circuit. Runs should be made with five or six values of the exciting current. The value of the field current while the machine is slowing down need not necessarily be the same as while speeding up. It is advisable, however, to keep it the same, because otherwise it takes too long for the current to settle to the desired value, on account of the high inductance of the field windings. In order to obtain high speeds, use for the armature a voltage higher than the rated voltage of the machine.

(*d*) To determine the constant C of the revolving part use either method described in § 286. With the first method, take a total-loss curve by driving the machine as a motor and measuring the input into the armature. Take this curve very carefully; keep the field current at exactly the same value as in one of the retardation curves, and vary speed within as wide limits as possible by varying the impressed voltage. With the second method connect a comparatively high resistance across the armature terminals, and provide a wattmeter for keeping watts delivered to this resistance constant. Take two special retardation runs with the same field current; keep the resistance closed in one run and open in the other. Read the speeds only as far as the power in the resistance can be kept constant.

(*e*) Before leaving the laboratory measure the resistance of the armature winding.

Report. Plot the observed retardation curves (Fig. 234), and calculate C as in § 286. Convert the retardation curves into the loss curves shown in Fig. 232, according to the directions given in § 285. The rest of the requirements are the same as in § 280.

SEPARATION OF HYSTERESIS AND EDDY-CURRENT LOSSES.

288. The curves shown in Fig. 232 give total losses and friction loss for various speeds and field currents. Subtracting friction loss from total loss gives core losses (hysteresis and eddy currents) for various speeds and values of the exciting current (Fig. 229). The next step is to separate hysteresis loss from eddy currents. This is done on the basis of the fact that, *with a given excitation, hysteresis loss is proportional to the speed, while eddy-current loss increases as the square of the speed.* The reason for this is as follows (see also §§ 168 and 169):

Hysteresis loss per second is proportional to the number of cycles of magnetization of the armature iron, and this number of cycles is equal to the number of times each piece of the armature passes by the poles of the machine, or, in other words, it is proportional to its speed. Eddy currents are induced currents, and, as such, are proportional to the speed of the machine; but the energy loss is proportional to the square of the current (I^2R); therefore, eddy-current loss is proportional to the square of the speed.

Thus, at a certain speed of n revolutions per minute,

$$\text{total iron loss } P = Hn + Fn^2 \quad . \quad . \quad . \quad . \quad . \quad (12)$$

where H and F are two constants characterizing hysteresis and eddy- (Foucault) current losses respectively.

This equation can be used for the separation of the losses in two ways, purely analytical and graphico-analytical; both solutions are given below.

289. Analytical Separation. — Select one of the curves in Fig. 229 and apply the above equation (12) to two points taken sufficiently far apart and corresponding to two values of speed, n_1 and n_2:

$$P_1 = Hn_1 + Fn_1^2;$$
$$P_2 = Hn_2 + Fn_2^2.$$

These equations can be easily solved for H and F. After this is done, the straight line Hn representing the hysteresis loss (Fig. 230) can be plotted, as well as the parabola Fn^2, giving the eddy-current loss (Fig.

231). The same procedure is then repeated for other curves in Fig. 229, and in this way hysteresis separated from eddy currents, for all conditions under which the machine may operate.

The disadvantage of this purely analytical method is that in selecting two points on a curve an assumption is made that these points are absolutely correct; in other words, that any two other points on the same curve would give exactly the same values for H and F. In reality, the values of H and F vary somewhat for different points selected on a curve. This means a tedious process of calculating H and F for several combinations of points and taking average values.

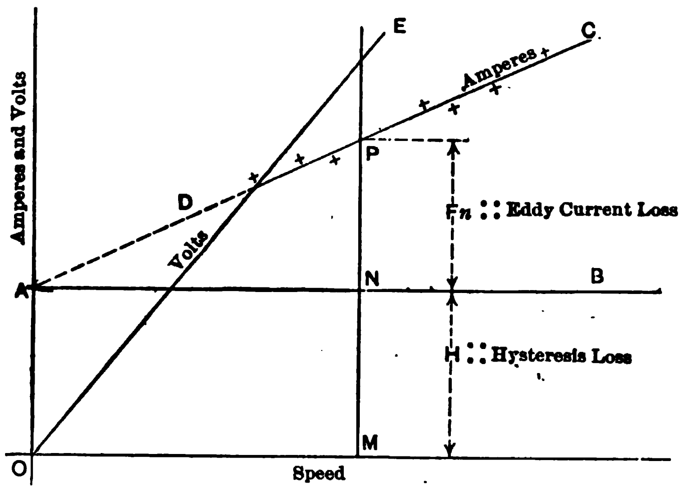

FIG. 236. Graphico-analytical method for separating hysteresis from eddy currents.

The graphico-analytical method permits of taking simultaneously into account as many points on a curve as desired; in this manner the most probable values of the separated losses are obtained in a simpler way.

290. Graphico-Analytical Separation. — Equation (12) may be written in the form

$$P = IE = IKn = Hn + Fn^2,$$

where K is a constant, since with a constant excitation the e.m.f. E of the motor is proportional to its speed; I is that part of the total armature current which is spent in overcoming hysteresis and eddy currents. Dividing both sides of this equation by n, we get

$$KI = H + Fn.$$

This is the equation of a straight line between the current I and the speed n. A line DC of this kind is shown in Fig. 236. By producing it to

the axis of ordinates, a horizontal line AB is obtained, which subdivides the ordinates of DC into the constant part MN proportional to the hysteresis constant H, and the part NP corresponding to eddy currents, and proportional to the expression Fn.

Each of these being multiplied by the voltage corresponding to the same speed and the same field current (ordinates of the line OE) gives the corresponding loss in watts. This completes the separation of magnetic losses.

An example will make this graphico-analytical method clearer. Let the iron-loss curve corresponding to 2 amperes field current (Fig. 229) be determined by the data given in the first two columns in the table below; the third column gives the corresponding armature volts, as shown by the curve OE in Fig. 236. Dividing watts by volts gives amperes iron loss (column 4); these values plotted against the speed give the straight line DC. This line is produced to the axis of ordinates,

1	2	3	4	5	6
Speed (r. p. m.)	Iron Loss Watts.	Arm. Volts.	Current Amps.	Hysteresis Watts.	Eddy Current Watts.
1800	1875	250	7.5	750	1125
1440	1320	200	6.6	600	720
1080	855	150	5.7	450	405
720	480	100	4.8	300	180
360	195	50	3.9	150	45
			Field current = 2 amp.		

and the part OA corresponding to hysteresis loss is found to be equal to 3 amperes. Multiplying this by the volts given in column 3, watts hysteresis loss is obtained (column 5). This loss, subtracted from total iron loss (column 2), gives eddy-current loss, (column 6). The data thus obtained are plotted as in Figs. 230 and 231.

291. Effect of Armature Reaction on Iron Loss. — Armature reaction (§ 127) affects not only the speed of a motor, or the generator voltage, but the iron loss as well. The armature reacts on the field so as to weaken or to strengthen it, and moreover distorts it, making it stronger at one end of the pole-piece and weaker at the opposite end. Thus, with the same field current, the actual magnetic flux is different in a loaded machine from that at no load; this naturally affects the iron loss, which depends on the flux density in different parts of the magnetic circuit. The practical result is that the actual efficiency of a machine under load is somewhat lower than that calculated from the losses.

A good deal has been written on the subject of the increase of iron loss with the load (*zusätzliche Verluste*, additional losses), but as no simple practical rules are available for taking this additional iron loss into account, it is usually left without consideration. The error committed is very small unless the machine is of a very poor design, and the armature reaction has abnormal proportions. Compensating poles for neutralizing armature reaction (Fig. 220) are coming more and more into use; in such machines the iron loss is the same at no load as with a load, and no correction is necessary.

292. Separation of Losses in Series Motor. — The determination of iron loss and friction in shunt-wound motors is simplified by the fact that the speed, with a given field excitation, is nearly constant, and the losses are approximately the same at no load as at any other load. It is entirely different with a series motor: here the speed at no load is many times higher than at full load; moreover, the field strength, and consequently the iron loss, depend on the speed and on the load, and these vary within wide limits. Therefore, the results obtained by running a series motor at no load are of no use at any other load.

This can be remedied by separately exciting the motor and varying its field strength independently of the speed, which latter is regulated by a rheostat in the armature circuit. By this method the series motor is really converted into a shunt motor, and iron loss and friction can be determined as explained above. The method can be somewhat modified, so as to make it more adapted for series motor, as follows: Two series of runs are made at no load; one for determining iron loss and friction *together;* another in which iron loss is negligible; in this way iron loss is separated from the frictional losses.

For the first series of runs the armature of the motor is connected in series with the fields as in actual operation, but is shunted around by a variable resistance. A suitable regulating rheostat is also inserted into the main circuit. In this way the field and the armature currents can be regulated at will either together or separately. The motor is run at no load, so that the input into the armature represents, as before, the sum of iron loss and friction. Having a resistance in parallel with the armature permits of having a strong field even with a small armature current; in this way the speed of the series motor is kept within reasonable limits at no load even with the normal voltage.

These losses depend on two independent variables: field current and speed. As the speed with a given field is proportional to the voltage at the armature terminals, it may be said that *iron loss and friction depend on the field current and the voltage at the armature terminals.* In order to plot curves, one of the variables must be kept constant during

each run. It is convenient to keep the armature voltage constant for each curve, and to vary the field current by means of the two above-mentioned rheostats. Several curves should be taken within as wide limits of armature voltages and field currents as possible.

The second series of runs is intended to give a curve of friction alone; this is done by simply connecting the armature and the field of the motor in series and running the machine at no load. The terminal voltage must be kept sufficiently low; otherwise the motor will run away. The motor takes very little current when running at no load; therefore its field is so weak that iron loss can be neglected and the whole input into the armature assumed to be equal to the friction loss. Note that this is not so with shunt motors, because there the field has its full value at no load as well as at any other load, and iron loss is not negligible under any circumstances.

Subtracting the values of friction obtained from this curve from the ordinates of the curves previously taken, curves can be plotted giving iron loss separately as a function of speed and field excitation.

The first series of runs gives not only the total losses, but also ampere-speed curves corresponding to various terminal voltages. For the latter curves, the current in the field winding is determining, since part of the armature current is shunted around. The voltages during the test are measured across the armature; in order to refer the curves to terminal voltages, due allowance must be made for the ohmic drop in the armature and the field.

For some further details of this method and sample curves, see *Electric Club Journal* 1904, pp. 170–174.

293. EXPERIMENT 13-F. — Efficiency of a Series Motor from its Losses. — The machine is wired up as a regular series motor (Fig. 213) and a variable resistance is shunted across the brushes. The resistance shown in the diagram in series with the field is used for regulating the main current. Have an ammeter in the main circuit, another in the armature circuit, and a voltmeter across the brushes. Run the motor at a high speed for at least 30 minutes to warm up the bearings.

(*a*) For the first series of runs (iron loss + friction) shunt the armature so that the greater part of the current passes around it. Keep the field current large enough so that the motor will not run away, and gradually cut the resistance out of the main circuit, if possible altogether. Adjust the conditions so as to have full rated voltage or more across the terminals of the motor, and a current in the field of a value about 25 per cent above the rated current of the motor. Read

field amperes, armature amperes, volts across the armature and speed.

Gradually reduce the current in the shunting resistance, at the same time regulating the main rheostat to keep a constant voltage across the brushes. Reduce the currents until the upper safe limit of speed is attained. Repeat similar runs with the terminal voltage equal to 80 per cent, 60 per cent, etc., of the rated voltage.

(*b*) For the second series of runs (friction alone) remove the shunting resistance, and run the motor light throughout the possible range of speeds. A considerable resistance must be kept all the time in the main circuit to prevent the motor from running away. Take readings of amperes, volts and speed.

(*c*) Measure the resistances of the armature and of the field windings.

Report. (1) Plot watts input into the armature (iron loss + friction) to speed as abscissæ, each curve referring to a constant voltage.

(2) Plot, on the same curve sheet, field amperes *vs.* speed, each curve for a constant voltage.

(3) Plot, on the same sheet, watts friction loss to speed as abscissæ.

(4) Subtract friction loss from the curves (1), and plot curves of iron loss separately to armature volts as abscissæ, each curve for constant amperes.

(5) Correct one of the curves (2) to represent the true ampere-speed curve at the rated voltage.

(6) Show, with a numerical example, how to use the above curves for calculating efficiency, torque and output of the motor at a certain current and at the rated voltage.

NOTE TO § 286. For a more convenient, purely electrical method of determining the moment of inertia of the revolving part see Dr. Kapp's article in the *Journal of the* (British) *Institution of Electrical Engineers*, 1910.

CHAPTER XIV.

DIRECT-CURRENT MACHINERY — OPPOSITION RUNS.

294. TESTS for determining the efficiency, voltage regulation, and temperature rise in electric generators and motors, without the expenditure of much energy, may be conveniently performed when two machines of about the same size are available. The machines are then loaded to their full capacity *on each other*, no power being wasted in outside resistances, or in a Prony brake. The machines are connected mechanically and electrically (Figs. 238 and 239), and driven so that one machine acts as generator, the other as motor. The motor drives the generator, while the latter supplies electric power back to the motor. This is called the opposition or the "pumping-back" method of testing machines.

If the machines were ideal — without losses — the set would be self-contained and would require no power from the outside to drive it. In reality, the losses in both machines must be supplied either by an auxiliary motor, a booster, or by connecting the set to a source of supply. The power supplied to the set from outside covers only the losses in both machines, and herein lies the economy of the method. Suppose, for instance, that two 500-kilowatt generators are to be tested at full load. Assuming the efficiency of each machine to be 90 per cent the shop line would have to supply $500 \div (0.90)^2 = 618$ kilowatts if one machine were to drive the other in the ordinary way, the second machine being loaded on resistances. When running the same two machines in opposition, the line has to supply only 10 per cent of the $500 + 500$ kilowatts, or only 100 kilowatts. If a small driving motor or a booster is used (Fig. 238), the losses in these machines must also be supplied from the line; but even then the power demand is several times less than with an ordinary load test.

Electrical conditions in a generator or a motor, run in opposition with another machine, may be adjusted so as to have full-load current and the rated voltage. Therefore the opposition, or the pumping-back method is used for determining efficiency, regulation and temperature rise of the machine, as these require running it under full-load conditions.

295. Mechanical Analogy to Opposition Runs. — The following analogy (Fig. 237) may make clearer the underlying principle of all opposition methods. Let it be required to determine the efficiency of a large crane or hoist under full-load conditions, when the circumstances are such, that there is not enough power to drive it at full load, but it happens that another identical hoist is available. The two hoisting drums are then belted, as shown in the sketch, so that when the hoist No. 1 lifts its weight P_1, the hoist No. 2 lowers its weight P_2. The weights are equal and correspond to the rated capacity of the hoists; the whole system is mechanically balanced. Without friction, a very small force would produce a movement in either direction. In

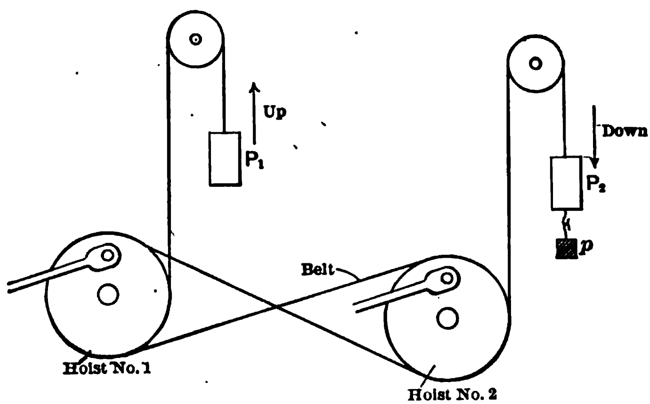

FIG. 237. A mechanical analogy illustrating the electrical opposition methods.

reality quite a considerable force is necessary to overcome the friction in both machines, and to start the movement.

This extra power may be applied either as a driving force on the shaft, or as an extra weight P added to the load of one of the hoists. The first solution is analogous to the auxiliary motor shown in Fig. 238, the second solution corresponds to power being supplied from the line, as in Fig. 239. In either case, efficiency is calculated from the ratio of the power supplied from the outside, to the load of the machines. Suppose, for instance, that each of the large weights on the hoists is 100 tons, and that an additional weight of 20 tons is required to move the system at its rated speed. This corresponds to a friction loss of 10 tons per hoist; the average load is 110 tons, consequently the efficiency of either hoist is

$$\frac{110-10}{110} = 91 \text{ per cent.}$$

296. Classification of Opposition Methods. — The methods by which two electrical machines may be run in opposition are usually classified according to the way in which the losses are supplied. Copper loss may be supplied electrically or mechanically, and iron loss + friction may also be supplied either electrically or mechanically. This gives the four combinations shown in the following table:

	Iron loss and friction supplied mechanically	Iron loss and friction supplied electrically
Copper loss supplied electrically	(1) Blondel	(3) Kapp — Parallel; Potier — Series; Hutchison — Series and Parallel
Copper loss supplied mechanically	(2) Hopkinson	(4) Impracticable (?)

Blondel's method (1) is theoretically the most rational, because electrical loss is supplied electrically, while mechanical losses are supplied mechanically; its disadvantage is that it requires a booster set and an auxiliary motor (Fig. 238).

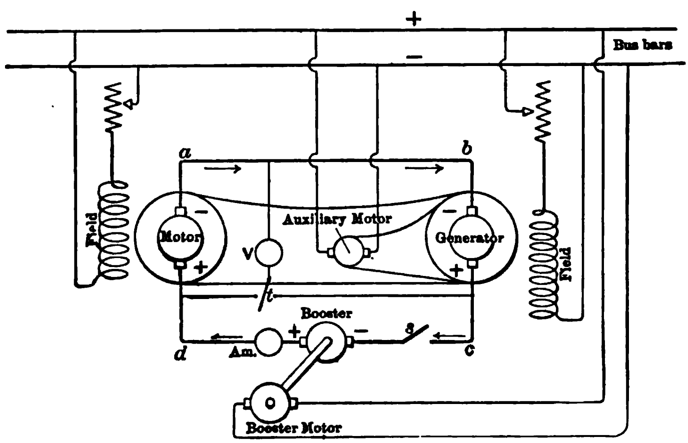

FIG. 238. Blondel's opposition method for testing two direct-current machines.

Omitting the booster set and supplying all the losses by the auxiliary motor gives Hopkinson's method (2); this method is as good as Blondel's for determination of temperature run and regulation, but gives only approximate results for efficiency.

On the other hand, omitting the auxiliary motor in the Blondel scheme gives the three methods marked (3) in the table (see Fig. 239). All the losses are supplied here electrically, either by a booster or directly from the line, or by both methods. The absolutely correct method among these three is that of Hutchison, in which copper loss is supplied by the booster, and iron loss + friction from the line.

Kapp omits the booster and supplies all the losses from the line; Potier does not use the line and supplies all the losses by the booster.

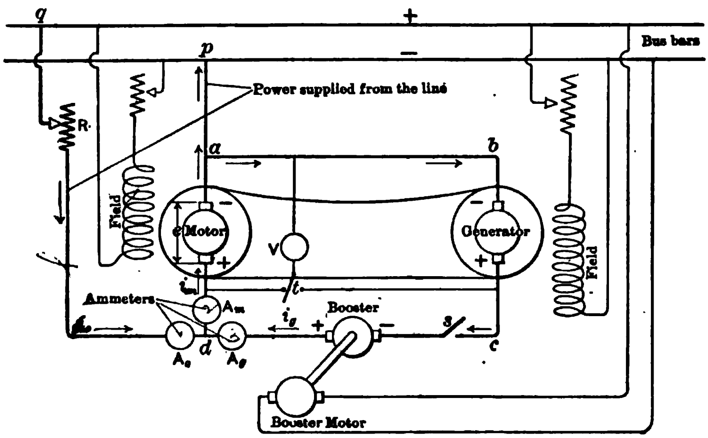

FIG. 239. Hutchison's opposition method for testing two direct-current machines.

These two methods are simpler than Hutchison's and just as good for temperature run and regulation, but give only approximate results for efficiency.

The method (4) has never been worked out in practice, for it does not seem rational to supply electrical losses mechanically, and vice versa. It may be possible, however, that a simple and satisfactory arrangement of this kind could be devised.

All the above methods will now be described more in detail.

297. Losses Supplied Electrically and Mechanically. — We shall begin with Blondel's method, as it is more correct theoretically, and moreover all other methods may be deduced from it. The connections are shown in Fig. 238. Two identical machines under test are belted or coupled together; their armatures are connected electrically in opposition. The fields should be excited separately, from the line, when-

ever possible. A small auxiliary motor is belted to one of the machines, and supplies the iron loss and friction of the set. A booster is connected in series with the armatures and generates the voltage necessary for overcoming the resistance drop in the two armatures. The booster is shown in the diagram driven by a separate motor.

The set is started and brought up to speed by the auxiliary motor with the switch *s* open. Then the fields of both machines are excited to the required value, and when the voltmeter *V* gives the same reading on both sides, the switch *s* is closed. Very little current flows between the two machines, the armatures being in opposition. By exciting the booster so as to add its voltage to that of the generator, any desired current may be made to circulate between the two machines. If there should be sparking on the commutators, the brushes should be shifted forward on the generator and backward on the motor, by equal amounts.

By regulating the field rheostats of the two machines, the speed of the auxiliary motor, and the booster voltage, any desired conditions of current, voltage, and speed of the set under test can be established. It is easily seen that the booster supplies the copper loss only, when both machines are equally excited; this is because the electromagnetic torque between the fields and the armatures is the same in the two machines, so that no excess of power is left on the belt for overcoming mechanical losses. On the other hand, the induced e.m.f.'s being also equal, the current is made to circulate only by the voltage supplied by the booster. Therefore, the copper loss is supplied entirely by the booster; consequently, iron loss and friction are supplied by the auxiliary motor.

298. Details of Blondel's Method. — Suppose that the machine under test (Fig. 238) is intended to be used in regular service as a generator. Then its speed and voltage during the test are adjusted to conform with the data on the name-plate, the load current being taken a little larger to account for the field current which during the test is supplied separately, but which, in regular operation, must be supplied by the armature itself. The test may be performed either for determining the efficiency, regulation, or temperature rise of the machine. We shall consider these three cases separately.

(*a*) *Efficiency.* The other machine must in this case be identical with the machine under test, or else its efficiency must be known. Assuming it to be identical, its fields must be excited to the same degree, in order to have the same iron loss in both machines; the current is adjusted to a proper value by the booster. Let *P* be the watts power supplied by the auxiliary motor, *I* the current circulating

between the machines, E the rated voltage of the generator, i the exciting current during the test, and e the voltage across the booster armature.

We have then:

useful output of the generator $= E\ (I - i)$;
iron loss + friction in each machine $= \frac{1}{2}\ P$;
copper loss in each machine $= \frac{1}{2}\ eI$;
excitation loss in each machine $= Ei$;

the latter includes the loss in the field rheostat.

$$\text{The efficiency of the generator} = \frac{E\ (I - i)}{EI + \frac{1}{2}P + \frac{1}{2}\ eI}.$$

The output of the auxiliary motor is determined from its input and losses (see latter part of § 275); all other quantities entering into this expression are measured directly during the test.

It is left to the reader to develop a similar efficiency formula for the case when the machines under test are intended to be regularly used as motors. The exact input corresponding to the rated horse-power output can in this case be determined only by trials; it is advisable to take readings within wide limits of input.

(b) *Regulation.* The adjustment is the same as before, but the machines do not need to be alike. Having obtained full-load conditions on the machine under test, reduce the booster voltage, or increase that of the other machine until the circulating current is reduced to zero, or, more correctly, to the value of the field current. This corresponds to throwing the load off the machine, as required for the regulation test (see § 224). Measure the terminal voltage under these conditions. Another way of determining the voltage at no load is to open the switch between the generator and the motor and to drive the generator at no load by the auxiliary motor. Per cent rise in voltage is, by definition, the regulation of the generator.

If the machine under test is intended to be used as a motor, and per cent speed regulation between no load and full load is required, keep the voltage across the motor terminals constant by means of the booster field, and reduce the speed of the auxiliary motor until the circulating current is reduced to zero, or, more correctly, to that which the motor takes at no load. Another way of accomplishing the same result is to throw off the belt between the two machines and to run the motor at no load.

(c) *Temperature Run.* The adjustment is the same as before; the machine under test must have the same current which its armature carries at full load, same field and the rated speed. The other machine

may be of any kind, provided it can take up the load delivered by the first machine. If the two machines are identical, the temperature run is made on both simultaneously.

Before beginning the run, cold resistances of the armature and the field must be measured. The machines are then run the required number of hours under load, and hot resistances are measured in order to calculate the temperature rise (§ 7). The temperature of the armature iron and of the commutator is measured by thermometers. Sometimes, the temperature of the windings is also measured by thermometers, as a check on resistance measurements.

299. EXPERIMENT 14-A. — Efficiency, Regulation, and Temperature Rise by the Blondel Opposition Method. — The machines are connected as in Fig. 238; instructions for starting the set are given in the preceding article. The runs for efficiency, regulation and temperature rise may all be performed during the same laboratory period. Perform these tests from the standpoint of the machine under test running as generator, and at the end of the test make a few runs assuming the machine under test to be a motor.

(*a*) Begin the experiment by measuring cold resistances of the generator and the auxiliary motor. Bring the set up to speed and adjust the current at about 25 per cent overload. Take the necessary readings, and then gradually reduce the armature current to zero, so as to obtain complete curves of efficiency and regulation. Read generator volts, booster volts, field current, circulating amperes, speed, and the input into the driving motor. The latter reading should comprise armature amperes, volts, field amperes and speed. At the end of the test, take off the belt, and run the driving motor light, in order to determine its own losses.

(*b*) Belt the motor again, bring the set up to speed, and adjust the conditions for the temperature run, so as to obtain an appreciable temperature rise in an hour or less. An average machine ought to be able to stand at least 50 per cent overload in current and 25 per cent over-potential for this period of time. At the end of the run, measure hot resistances and temperature rise by thermometers.

Report. Plot curves of efficiency and voltage regulation to amperes output as abscissæ. Give the data observed on temperature run.

300. Losses Supplied Mechanically — Hopkinson Method. — The above-described Blondel method of running two machines in opposition requires an auxiliary motor and a booster set. If it is desired to do away with the booster, the current between the two machines may be circulated by weakening the field of one, or by strengthening the

field of the other. In this case the auxiliary motor (Fig. 238) supplies the copper loss as well as the iron loss and friction of the set. This method is simpler than Blondel's, and is quite commonly used in testing departments of electric manufacturing companies. The only objection to the method is that the iron loss in both machines is not the same, the fields being differently excited. This, however, is of no consequence for regulation and for temperature tests, as in this case the two machines need not be entirely identical. The method gives only approximate results for efficiency, but efficiency is usually determined from the losses and not from an opposition test.

When a temperature run is required on both machines, each is run as motor half of the time, to make the conditions the same. The difference between the true iron loss in the two machines is not so large as may appear from the difference in the exciting currents. With the proper setting of brushes, the field of the generator is weakened by the armature reaction, while that of the motor is strengthened, bringing them nearer to each other.

If P is the output of the auxiliary motor, total losses in each machine may be assumed to be $\frac{1}{2}$ P and

$$\text{efficiency} = \frac{(I - i)\,E}{IE + \frac{1}{2}P}$$

(see § 298). A similar formula may be deduced for the case when the machine under test is intended to be used as a motor.

301. EXPERIMENT 14-B. — Efficiency, Regulation, and Temperature Rise by the Hopkinson Opposition Method. — The method is explained in § 300; the directions for performing the experiment are similar to those in § 299.

302. Losses Supplied Electrically—Hutchison Method.—The losses may be supplied by the three methods enumerated under (3) in the table above. The theoretically correct method for determining efficiency is that of Hutchison, where the losses are supplied partly in series, partly in parallel. The connections are shown in Fig. 239. The method is similar to that of Blondel (Fig. 238), except that the auxiliary motor is dispensed with, and iron loss + friction is supplied directly from the line pq, through the wires ap and dq.

The set is started from the line with the rheostat R, using the left-hand machine as a motor, the switch s being open. When the machines are up to speed, the generator field is excited, and when the voltages of the two machines are approximately equal, the switch s is closed. After this the required current is established between the two machines by suitably exciting the booster.

The field current must be the same in the two machines, at least for the efficiency test, in order to have the same iron loss. Copper loss is supplied by the booster, as in the Blondel method. It is shown below that the line supplies not only iron loss and friction, but also a small part of the copper loss; the correction is easily applied, and does not impair the accuracy of the method.

Kapp's method is obtained from that of Hutchison by omitting the booster; all the losses are supplied directly from the line. A current is made to circulate between the two machines by weakening the motor field. This method has an advantage of a greater simplicity, and is just as satisfactory for regulation and temperature runs. It does not give quite correct values for efficiency, both the iron loss and the copper loss in the two machines being different.

Potier's method is obtained from that of Hutchison by omitting the connections to the line and supplying all the losses from the booster. The field of the motor must in this case be stronger than that of the generator, in order to give it an additional torque for overcoming the iron loss + friction of the set. With this method the copper loss in both machines is the same, but the iron loss is somewhat different; the same remark applies to it as to Kapp's method.

303. Efficiency by Hutchison Method. — If Ei_o is the power delivered to the set from the line (Fig. 239), and ei_g that delivered by the booster, the expression $\frac{1}{2}(Ei_o + ei_g)$ represents total losses in each machine (assuming the losses equal), and the efficiency may thus be easily determined. This is, however, not quite correct, because the currents i_g and i_m in the two machines are somewhat different. If a greater accuracy is required, the copper loss should be figured out separately, as shown below.

With the notation shown in the diagram, we have

$$Ei_o + ei_g = i_g^2 r + i_m^2 r + P \quad . \quad . \quad . \quad . \quad . \quad (1)$$

This equation expresses that the power Ei_o supplied from the line, plus the power ei_g delivered by the booster, is equal to the copper loss in the armatures of the two machines, plus their iron loss and friction P. The fields being equally excited, the voltages induced in the two armatures are equal and opposite. Therefore, the booster voltage must be equal to the voltage drop in the armatures of both machines, or,

$$e = i_g r + i_m r \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The current i_o supplied from the line is the difference between the motor current i_m and the generator current i_g, or

$$i_o = i_m - i_g \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Substituting e and i_g from (2) and (3) into (1), we get

$$P = Ei_o - i_m i_o r \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

In other words, iron and friction loss, P, of the set is equal to the power Ei_o supplied from the line, less a correction $i_m i_o r$. The iron and friction loss in each machine is $\frac{1}{2}$ P. The copper loss in the armature of either machine may easily be calculated from the ammeter readings, and the efficiency thus determined (taking account of the excitation loss).

304. EXPERIMENT 14-C.—Efficiency, Regulation, and Temperature Rise by the Hutchison Opposition Method. — The theory and the directions are given in §§ 302 and 303. The order in which the experiment is performed, and the requirements for the report, are the same as in § 299. At the end of the test, disconnect the line at p and q and run the set by supplying all the losses from the booster; this is Potier's method, mentioned in § 302. Then disconnect the booster and supply all the losses from the line; this is Kapp's method mentioned in the same article.

305. Opposition Runs on Series Motors. — The methods given in the table (§ 296) with corresponding changes may be used for testing series motors, more particularly railway motors. Such motors are tested in large quantities, and it pays to provide special arrangements in order to facilitate handling the machines.

One of the methods used by the General Electric Company is similar to that shown in Fig. 238, except that the motors, instead of being belted together, are geared to a countershaft. This shaft is driven by an auxiliary motor, which supplies mechanical losses. The fields are connected in series with the armatures, and a booster supplies the copper loss.

A simpler method, which is a modification of Kapp's method, is shown in Fig. 240. The motors are coupled together and are connected electrically in opposition. The motor to the left is started from the line and drives the other machine, which acts as a generator and supplies current to the water rheostat; the switch S_1 is open. When the proper speed is reached, and the voltmeter V_1 shows nearly zero, the switch S_1 is closed. By increasing the resistance in water rheostat, the generator is made to send part of the current back into the motor, reducing the current drawn from the line. Finally the circuit-breaker S_2 is opened, and the machines run in opposition.

Shunting rheostats R_1 and R_2 are provided around the field windings F_1 and F_2, in order to regulate the speed of the set and the current circulating between the machines. The machine with a weaker field acts as a motor, the other as generator. To make the conditions

during the temperature run equal, each machine is made to act half of the time as generator, and half of the time as motor.

306. EXPERIMENT 14-D. — Opposition Run on Two Series Motors. — Two identical railway motors are connected according to either scheme described in § 305 and run throughout the possible range

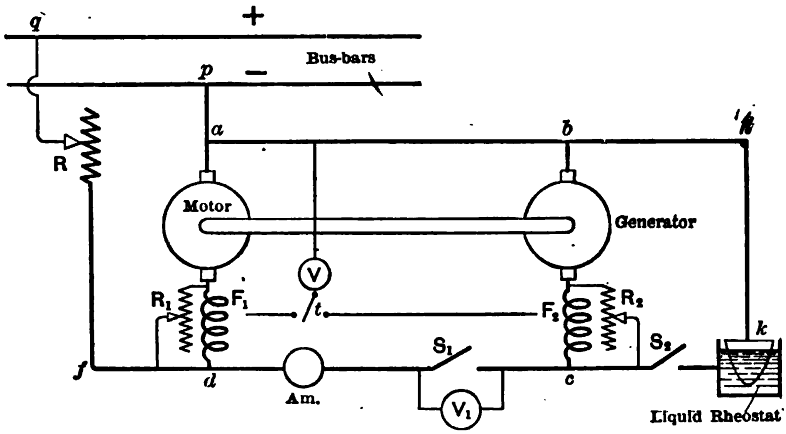

FIG. 240. An opposition test on two series-wound motors.

of speeds, the purpose of the test being to obtain ampere-speed and efficiency curves. After this, a heavy overload is put on the motors for about an hour (temperature run). Measure cold and hot resistances, and also determine temperature rise by thermometers.

Report. Plot ampere-speed and efficiency curves of the motor; give temperature rise by resistances and by thermometers.

CHAPTER XV.

THE TRANSFORMER — ELEMENTARY EXPERIMENTS.

307. A TRANSFORMER is a device used for raising or lowering voltage in alternating-current circuits (Fig. 241). Its principal application is in power-transmission plants and in distribution of power by means of alternating currents. Aside from this, transformers are used in some cases for regulating voltage (Fig. 437), and for measuring purposes (Fig. 45).

A transformer consists of two windings placed on the same iron core (Fig. 241); one winding — the primary — is connected to the power supply, the other — the secondary — to the load. The primary alternating

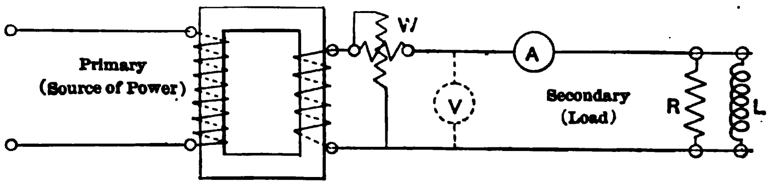

FIG. 241. Diagram of connections for loading a transformer.

current produces in the core an alternating magnetic flux, which in turn produces induced voltage and, consequently, currents in the secondary winding. By properly selecting the number of turns in the two windings, the voltage may be raised or lowered.

308. Core-Type and Shell-Type Transformers. — There are two ways of arranging the windings and the iron core relative to each other: the core is placed either inside the coils or it surrounds them. The first construction, the so-called *core-type transformer*, is shown in Fig. 242. The primary and the secondary coils surround the core, and are placed as close as possible to each other, in order to obtain a more perfect inductive action and to minimize magnetic leakage. Transformers are usually immersed in oil, which keeps the transformer cooler in operation and also protects its insulation from moisture and deterioration.

A *shell-type transformer*, or one in which the iron core surrounds the coils, is shown in Fig. 243; the details are the same as in the core-type transformer.

Electrically the two types are equivalent, the difference being merely in the mechanical construction. Both types are used by different manufacturers, and some companies build transformers of either type.

309. Ratio of Voltages and Currents. — The fundamental property of the transformer is that the ratio of currents primary and secondary is practically equal to the inverse ratio of the corresponding voltages. This can be explained in two ways:

(*a*) As the losses in a transformer amount to only a few per cent of its rated capacity, it follows that practically all of the power supplied to the primary is delivered to the secondary. This power is measured by the product "volts times amperes," and so we have, to a very close approximation:

$$E_1 I_1 = E_2 I_2,$$

whence

$$\frac{I_1}{I_2} = \frac{E_2}{E_1},$$

where E_1 and E_2 are the primary and the secondary voltages, and I_1 and I_2 the corresponding currents.

(*b*) Another explanation is based on the fact, that the current necessary to magnetize the transformer iron is very small (closed magnetic circuit, low flux density); therefore the number of primary ampere-turns n_1 is practically equal to the opposing number of secondary ampere-turns n_2, or

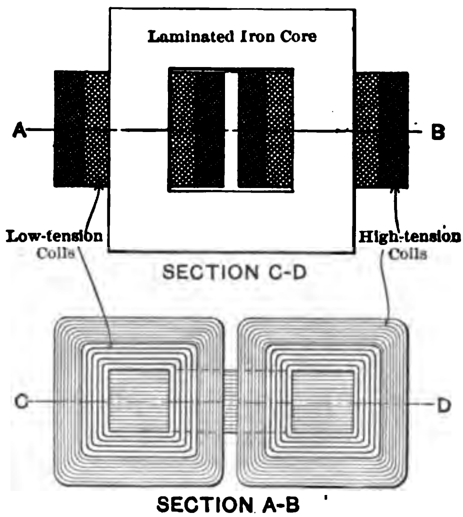

FIG. 242. A core-type transformer.

$$I_1 n_1 = I_2 n_2.$$

But in a transformer, as in any other apparatus based on induction, voltages are proportional to the number of turns, and we have again that

$$\frac{I_1}{I_2} = \frac{n_2}{n_1} = \frac{E_2}{E_1}.$$

310. EXPERIMENT 15-A. — **Ratio of Voltages and Currents in a Transformer.** — The purpose of the experiment is to make clear the numerical relations outlined in the previous article. It is well to have, for the experiment, a transformer with several taps, at least on

one of the windings (Fig. 244), so as to be able to vary the number of active turns, and consequently the ratio of voltages and currents.

(*a*) Connect the primary winding to the supply, the secondary winding to a load; have an ammeter and a voltmeter inserted on both sides, or transfer the same instruments from one circuit to the other by means of suitable switches. Vary the load from zero to a maximum, and read volts and amperes on both sides.

(*b*) If possible, change the ratio of turns, and repeat the same experiment. Make one of the runs with an inductive load, say a choke coil, in order to see if the ratio of currents remains the same. Before leaving the laboratory, inform yourself as to the number of turns in the two windings.

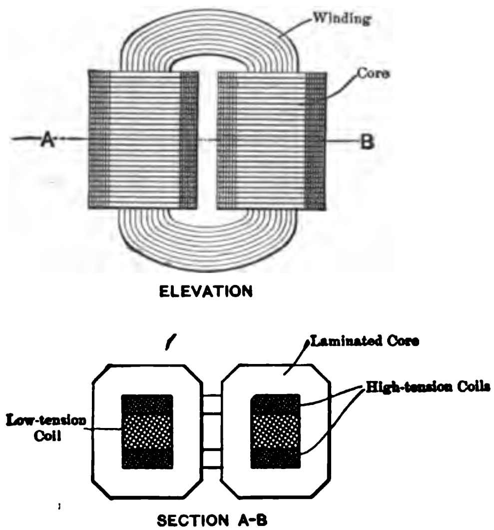

FIG. 243. A shell-type transformer.

(*c*) If two transformers are available, a complete power transmission may be realized in the laboratory. The voltage is stepped up, say from 110 volts to 2200 volts, and then stepped back at the other end of the line to 220, or any other desired voltage. For reading line volts, the voltmeter must be provided with a shunt transformer of a known ratio (Fig. 45).

Report. (1) Plot to amperes load as abscissæ: primary amperes, primary volts and secondary volts; also a curve of ratios of volts and of amperes. Show that the ratio of volts is very nearly the same as that of the number of turns, and as the inverse ratio of currents. The ratio of currents may be somewhat different at light loads, because the transformer consumes a small primary current, even with no current in the secondary. This so-called no-load current serves largely for magnetizing the transformer iron, and has a small component for supplying the core-loss. (2) Describe the experiment on power transmission with step-up and step-down transformers, and give the numerical data observed.

311. Voltage Drop in Transformers.—In the above discussion, the transformer windings are supposed to be ideal, possessing no resist-

ance or reactance. In reality, when currents flow through the transformer, a certain drop takes place in its windings, so that if the primary voltage is maintained constant, the secondary voltage drops, as the load increases.

Suppose, for instance, that a transformer has such a ratio of the number of turns as 20 to 1. With the primary connected to a 2200-volt supply, the secondary voltage at no load is 110 volts. Suppose the voltage drop in the primary winding to be 2 per cent, or 44 volts at full load. This leaves 2156 volts to be transmitted into the secondary; with the ratio of transformation of 20 to 1, the secondary induced voltage is 107.8 volts. If the drop in the secondary winding is also 2 per cent, the voltage at the secondary terminals is but 105.6 volts, instead of 110 volts available at no load. Thus, as the load changes, the voltage fluctuates, producing an undesirable flickering of the lamps. Incandescent lamps are sensitive to a very few per cent variation of the rated voltage; therefore, good inherent regulation of transformers is of great practical importance.

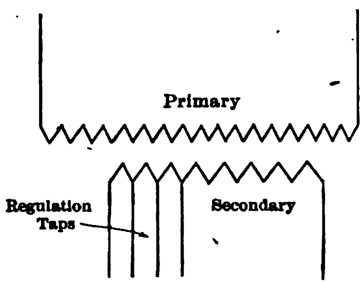

FIG. 244. Taps on a transformer winding, for voltage regulation.

Voltage drop in a transformer depends not only on amperes load but also on the power factor of the load. The explanation is the same as in Fig. 359 for transmission lines, and in Figs. 251 and 252 for alternators.

Voltage variation on the secondary side, with a constant primary voltage, may be determined either by actually loading the transformer, or it may be calculated from the measured resistances and reactances of the transformer windings. The second, or the indirect, method is always preferred in practice, because it gives more accurate results and involves but a small expenditure of power. This method is described in §§ 499 and 502. In order, however, that the student may see a transformer in actual operation and be able to judge concerning the magnitude of voltage fluctuations, he should determine the regulation by actually loading a transformer on ohmic and inductive resistances, as described in the next experiment. It is advisable to determine the regulation of the same transformer by the direct and the indirect methods in order to be able to compare the results.

312. EXPERIMENT 15-B. — Loading a Transformer. — The purpose of the experiment is to determine the fluctuations of secondary volt-

age with inductive and non-inductive load. There should be provided for this test an ordinary lighting transformer, such as is used in cities for stepping the 2200-volt supply down to 110 volts or 220 volts for light and power in houses.*

The test consists in actually loading the transformer and varying the load and its power factor. Voltages must be measured very accurately, because the drop between no load and full load is but a few per cent. The best way to measure the primary voltage is to have another transformer connected to the same primary circuit and kept unloaded. The voltmeter should be provided with a double-throw switch to enable one to read quickly in succession the voltages of both loaded and the unloaded transformers. This is better than actually throwing off the load for measuring the no-load voltage, because this may somewhat change the primary voltage.

A shunt or potential transformer (Fig. 45) may be used with the voltmeter, for reading the voltage on the high-tension side. An ammeter and a wattmeter must be connected on the low-tension side, as shown in Fig. 241; it is well to have an ammeter on the high-tension side, that it may be possible to check the ratio of currents. First determine the regulation at non-inductive load. The primary volts must be kept constant; the secondary voltage decreases, as the load increases. If it should be impossible to keep the primary volts absolutely constant, the secondary volts must be corrected before plotting the curves; within the limits of fluctuations it can be safely assumed that the secondary voltage is directly proportional to the primary, so that if, for instance, the primary voltage was 2 per cent low when a reading was taken, the observed secondary voltage must be also increased 2 per cent before plotting the regulation curve.

After this test the regulation of the transformer must be investigated on inductive loads. With non-inductive load there is but one quantity to be varied, viz., amperes (or, which is the same, watts); on inductive loads there are three variables: amperes, watts and power factor. Any two of these can be taken as independent, and curves plotted giving the regulation of the transformer, say for constant watts, constant current or a constant value of the power factor. It is much easier to regulate the inductive and non-inductive resistances so as to keep either amperes or watts constant and to get the influence of the power factor on regulation.

* If the distributing network is laid underground (cables), such transformers are usually placed in the basements of the houses; if the distribution is done by means of overhead wires, the transformers are mounted on the outside of one of the walls, or on a pole near the house.

NOTE. A student working with a 2200-volt transformer must remember that *it is dangerous* to come in contact with the high-pressure side of it; great care should be exercised in regard to touching any switches, wire, or instruments connected to the high-tension side. Rubber matting should be put on the floor for protection, so as to insulate the students from the ground, and the students should not touch either the walls, pipes or any objects that might be connected to the ground. In addition, rubber gloves should be provided for the student who reads the high-tension instruments, so that he could not touch them by mistake. *Directions of the instructor should be followed exactly,* and no changes attempted before consulting him.

An electrical engineer has to handle high-tension currents in his practical work, and it seems, therefore, natural that he should have some experience with it before leaving college; he should know, however, that a mistake or negligence may prove fatal, and should act accordingly.

(*a*) Apply a certain load, say 25 per cent overload, entirely non-inductive, and gradually decrease it, at the same time introducing more and more of an inductive load, — say a choke coil in parallel with the rheostat. Regulate the load so as to keep *total amperes constant,* and observe the variation of the secondary voltage as the power factor decreases. The same test can be repeated for 100 per cent load, 75 per cent load, etc.

(*b*) Now again take a certain non-inductive load and gradually add to it some inductive load, keeping *total watts constant.* Observe the regulation under these conditions. In this case it may be better to begin with the lowest power factor available (largest current), as otherwise the ammeter and wattmeter may be overloaded and damaged. Several curves should be taken, for various values of watts. A data-sheet, similar to the one shown below, is convenient for recording the readings.

	NON-INDUCTIVE LOAD.					INDUCTIVE LOAD. . . . AMPS. CONST.					
	Prim. Amps.	Prim. Volts.	Sec. Amps.	Sec. Volts.	Sec. Watts.	Prim. Amps.	Prim. Volts.	Sec. Amps.	Sec. Volts.	Sec. Watts.	Power Factor.
Inst. No.											
Const.											
	....	....	....	....	....	....	....	....	....	....	....
	....	....	....	....	....	....	....	....	....	....	....
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Report. Give the actual connections used during the experiment. Plot to power factor as abscissæ, curves of volts for constant amperes,

as indicated in Fig. 253 in application to alternators. Plot on the same sheet curves of corresponding watts. As voltage drop in transformers is quite small, use a suppressed volt scale, or plot volts drop instead of the voltage itself. On another curve sheet plot similar curves for the tests in which watts were kept constant, showing also the corresponding amperes. Figure out per cent regulation at full non-inductive load, as per definition given in § 319.

313. Auto-Transformer. — It is not absolutely necessary to have, in a transformer, two separate windings; the line voltage may be changed by having one winding connected across the line, *and the load taken from a part of the same winding*, as in Fig. 245. The voltage across AB is to the voltage across BC as the ratio of the numbers of turns between these points. If, in addition to C, other taps are provided, as shown in the sketch, the secondary voltage may be varied within certain limits.

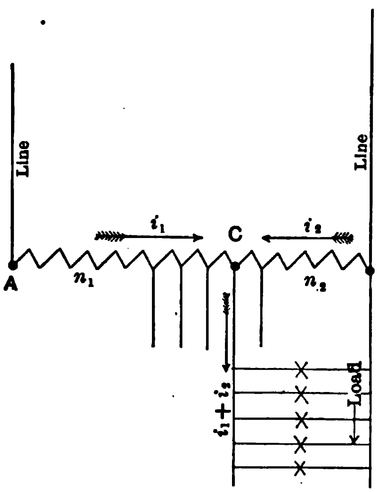

FIG. 245. A loaded auto-transformer.

Such a transformer with only one winding is called an *auto-transformer.* Theoretically it requires less copper than an ordinary transformer of same capacity. Its disadvantage is, however, that the high-tension and the low-tension windings are not insulated from each other. This excludes it from being used on ordinary lighting circuits where voltage is stepped down from 2200 volts. Auto-transformers are widely used for starting induction motors (Fig. 269) and for various purposes of regulation.

In an ordinary transformer a primary and a secondary current are distinguished. With an auto-transformer there are three different currents: current i_1 in the line and in the part AC in the transformer; current i_2 in BC, and the load current $(i_1 + i_2)$. The currents i_1 and i_2 are shown flowing in opposite directions, for the reason that the secondary current always opposes the primary in its magnetic action. We have then, as in § 309, that $n_1i_1 = n_2i_2$, where n_1 and n_2 are the numbers of turns in AC and BC.

Suppose, for illustration, that an auto-transformer has 120 turns between A and B, and the point C is so selected that there are 40 turns in the part BC. If the line voltage is 300 volts, the voltage across the

load will be only 100 volts. The part AC has 80 turns as against 40 in BC; therefore the current i_1 needs to be only one-half of i_2 in order to produce the same magnetic action. If the load current $(i_1 + i_2)$ is equal to 60 amperes, two-thirds of it, or 40 amperes, are supplied by i_2, and one-third, or 20 amperes, supplied by i_1. With this distribution of currents, the same energy is delivered to the secondary as is supplied by the primary, no energy being created or lost in the transformer itself:

$$\text{Power} = 60 \times 100 = 20 \times 300 = 6000 \text{ watts.}$$

In general, if e_1 and e_2 are the line voltage and the load voltages respectively, four electrical conditions must be fulfilled in an auto-transformer:

$$\begin{aligned} n_1 i_1 &= n_2 i_2; \\ e_1 \div e_2 &= (n_1 + n_2) \div n_2; \\ \text{load current} &= i_1 + i_2; \\ e_1 i_1 &= e_2 (i_1 + i_2). \end{aligned}$$

The load current, flowing back to the point B, is divided again into i_1 and i_2; the former returns to the line, the latter circulates between the winding BC and the load.

An auto-transformer may be used for raising voltages as well as for lowering voltages. If, for instance, the voltage of the line is 100 volts, the line may be connected to the points B and C, and a voltage of 300 volts made available between A and B.

314. EXPERIMENT 15-C. — Loading an Auto-Transformer. — The purpose of the experiment is to illustrate the relations of the preceding article. The experiment is performed in a manner similar to experiment 15-B above. Use an auto-transformer with regulating taps, or one winding of an ordinary transformer, if it is provided with taps. In some cases an auto-transformer may be improvised by connecting in series the two windings of an ordinary transformer.

(*a*) First determine the ratio of voltages without load. Connect the two outside points of the winding to the source of supply, and measure the voltages between the various taps. Also apply a voltage across a part of the winding, and read the higher voltage resulting across the total winding. In doing so, be careful to have enough turns in the part of the winding connected across the line, so as not to draw an excessive current.

(*b*) Connecting to a suitable tap, load the transformer, as in Fig. 241, having ammeters connected so as to read the primary and the secondary currents and the current in the load. One voltmeter and one ammeter in connection with a polyphase board (§ 49) are sufficient

for the purpose. Gradually increase the load from zero to a permissible maximum, reading all the currents and voltages.

(*c*) Repeat the same experiment with a few other taps, taken nearer to *A* or to *B*. In the latter case, be sure not to overload the part *BC* of the winding, as the current i_2 increases inversely to the number of turns. Before leaving the laboratory ascertain the number of turns between the various taps.

Report. Make a diagram of connections, and write on it per cent voltage at different taps. Plot i_1 and i_2 to load amperes as abscissæ, for a few taps. Show that the four conditions mentioned in the previous article are fulfilled.

315. Efficiency from Losses. — The efficiency of an electrical apparatus is, by definition, the ratio of its net power output to its gross power input. Thus, for instance, let the output of a transformer be 1200 kw. and the corresponding input 1223 kw. Then the efficiency at this particular load is $1200 \div 1223 = 98.1$ per cent. If there were no losses in the transformer, the input would be equal to the output, according to the law of conservation of energy; the efficiency would be equal to one hundred per cent at all loads. In the above-mentioned example, the losses amount to $100 - 98.1 = 1.9$ per cent of the input. This shows the close relation between the efficiency and the losses.

It may seem at first that the simplest way for measuring the efficiency of a transformer would be to have it actually loaded and to read the output and the input by means of wattmeters in the primary and in the secondary circuits; their ratio would give directly the efficiency of the transformer. However, this direct method has serious drawbacks, and is hardly ever used in practice. It involves the use of a wattmeter on the high-tension side; it requires an utmost accuracy of calibration of the wattmeters because the difference in the values to be read is but a few per cent. Moreover, with large transformers the amount of power required for a full-load test is not always available. Therefore, it is customary to measure the losses in a transformer separately (at no load), and then to *calculate* the efficiency. This can be done with much simpler means and with a considerably greater accuracy than is possible with the direct method.

The losses in a transformer consist of I^2R or copper losses in both windings, and of iron loss, also commonly called *core loss* (hysteresis and eddy currents). Copper loss depends on the load exclusively, and can be easily calculated for any load, if the resistances of both windings are known. Iron loss depends only on the magnetic flux, and is practically independent of the load. This follows from the fact that, the

impressed voltage being constant, the flux is also nearly constant (neglecting the primary drop). Therefore the iron loss can be determined at no load and assumed to be the same at all loads. Resistances are usually measured by the drop-of-potential method; core loss is determined from the no-load reading of the wattmeter.

As an illustration, suppose that it is required to determine the efficiency of a 2200 to 110-volt, 5-kw. transformer at $\frac{3}{4}$ load. Let the resistances of the windings be 10.7 ohms and 0.026 ohm respectively, and the iron loss, as determined by a wattmeter at no load, be equal to 96 watts. At three-quarters load the output of the transformer is 3.75 kw., or 34.2 amperes at 110 volts. The primary current is $\frac{1}{20}$ of this, or 1.71 amperes; thus we have:

$$\begin{array}{lll} \text{Primary copper loss} & = \overline{1.71}^2 \times 10.7 & = 31.2 \text{ watts.} \\ \text{Secondary copper loss} & = \overline{34.2}^2 \times 0.026 & = 30.4 \text{ watts.} \\ \text{Iron loss} \ldots & & = 96 \text{ watts.} \\ \hline \text{Total losses at } \frac{3}{4} \text{ load} & & 157.6 \text{ watts.} \end{array}$$

$$\text{Efficiency} = \frac{3750}{3750 + 157.6} = \text{about 96 per cent.}$$

In this way, data for any load may be obtained, and an efficiency curve may be plotted from no load up to, say, 50 per cent overload.

316. EXPERIMENT 15-D. — Efficiency of a Transformer from its Losses. — The experiment comprises three distinct measurements:

(1) Ratio of transformation;
(2) Resistances of windings;
(3) Core loss.

The ratio of transformation is determined by voltmeters, as in § 310. The resistances of the windings are measured with direct current, by the drop-of-potential method. As the resistance of the low-tension winding is usually much smaller than that of the high-tension winding, it may be necessary to use different ammeters and voltmeters. Always removet he voltmeter leads when opening or closing the circuit especially on the high-tension side; the inductive kick may damage the instrument.

The core loss is measured by a wattmeter, as in Fig. 162. It is not necessary to measure it from the high-tension side; 110 volts applied on the low-tension side produce the same flux and give the same core loss as 2200 volts applied on the high-tension side. Take curves of core loss and magnetizing current from zero voltage to about 50 per cent over-potential. In performing this measurement, be sure to disconnect the

high-tension side from the power supply, in order not to make a short circuit. Also remember that high-tension terminals become alive the moment a voltage is put on the low-tension terminals; in order to avoid the possibility of a fatal mistake, it is best to have the high-tension leads taped up.

Report. Give the ratio of transformation, the resistances of the windings, and plot curves of magnetizing current and iron loss to volts as abscissæ. Plot an efficiency curve and separate losses, to kilowatts load as abscissæ, up to 50 per cent overload. Indicate by crosses on the same curve sheet the values of efficiency at full load, and of the losses, when the supply voltage is 10 per cent above or below rated.

NOTE. For commercial tests on transformers see Chapter XXIV in Volume II.

CHAPTER XVI.

THE ALTERNATOR — OPERATING FEATURES.

317. An alternator is an electrical machine for producing alternating currents. The essential parts of a modern alternator are shown in Fig. 246. It consists of a stationary armature in which currents are induced, and of the revolving magnetic poles whose function it is to induce these currents. The exciting current, which energizes these magnet poles, is conducted into the revolving part through the two slip rings shown.*

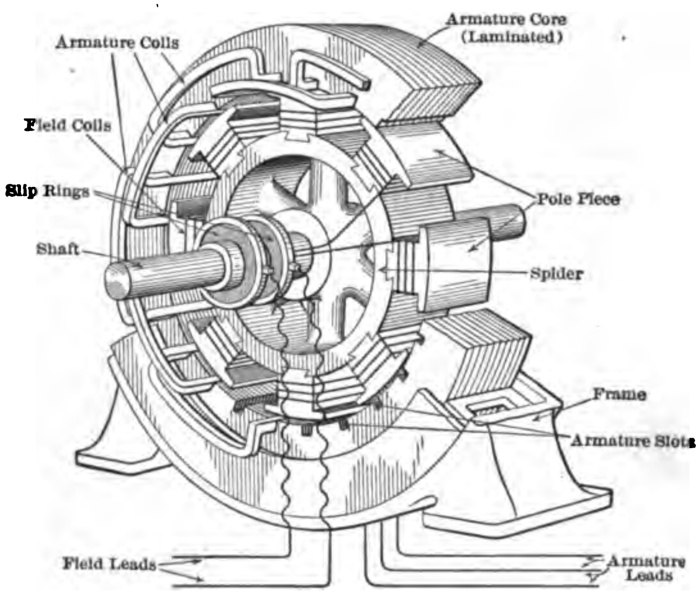

Fig. 246. The principal parts of an alternator, or of a synchronous motor.

The particular alternator shown in the sketch is an eight-pole, three-phase machine; it has four armature coils for each phase, or one side

*There is a type of alternator, so called *inductor* type, in which both the exciting and the armature windings are stationary; the pole projections alone are rotated, and the e.m.f. is induced, due to periodical changes in the reluctance of the magnetic circuit.

of a coil under each pole. Part of the coils have their free ends bent upward to leave room for the other coils. The armature core is laminated and is held together by a cast-iron frame.

By varying the speed of the machine, the frequency of the generated voltage is varied: for instance, the above machine, when driven at a speed of 900 r.p.m., gives 7200 alternations per minute, or 60 cycles per second. Whenever a pole passes under a conductor it produces one impulse, or one alternation. With 8 poles, 8 alternations are produced during one revolution of the machine, or $8 \times 900 = 7200$ alternations in one minute. One positive and one negative alternation give one complete period of alternating current; thus 7200 alternations make 3600 periods (or cycles) per minute, or 60 cycles per second. For a description of direct-reading frequency indicators see § 555 in the second volume.

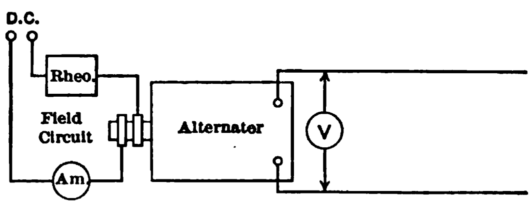

FIG. 247. Diagram of connections of a single-phase alternator at no load.

318. EXPERIMENT 16-A. — No-Load Characteristics of an Alternator.—The purpose of the experiment is to investigate the dependence of the voltage of an alternator on exciting current and speed. If the machine is a single-phase alternator, it is wired up as in Fig. 247; for three-phase connections see § 520. It is preferable to perform this experiment on a single-phase machine because the relations to be investigated are the same as in a polyphase machine, while the wiring and the measurements are much simpler.

Run the machine at its rated speed and increase the field excitation in steps; read the corresponding alternating voltages and field amperes. Take readings also with decreasing field current, so as to eliminate the influence of residual magnetism. Repeat the same test with a higher and a lower speed. A frequency meter, if available (see § 555), should be used to give direct readings of frequency. It is also convenient to have a tachometer, in order to keep the speed constant.

Report. Give a short description of the machine, and plot the voltage curves to field amperes as abscissæ (Fig. 194). Figure out the corresponding frequencies in alternations per minute and in cycles per second. Show that with the same exciting current the induced voltages are proportional to speed.

319. Load Characteristics of Alternators. — When a load is put on an alternator, as in Fig. 248, the terminal voltage decreases, because of a voltage drop in the machine itself. This drop depends upon the magnitude of the load and on its power factor. Therefore, when the load varies, the terminal voltage fluctuates.

One of the most important problems in the operation and design of alternators is that of reducing the fluctuations of the voltage with varying load. These fluctuations are particularly objectionable on lighting circuits, because of the accompanying flickering of the lamps. Therefore, certain requirements and guarantees in regard to the maximum fluctuations in voltage are usually introduced into contracts regarding the performance of alternators. These requirements are now usually stated in accordance with the recommendations of the American Institute of Electrical Engineers, in the form of a guarantee

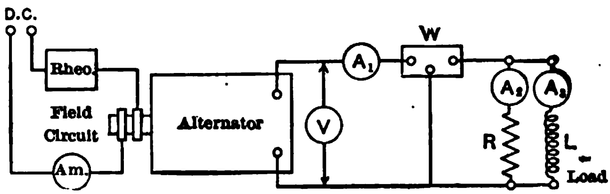

FIG. 248. Diagram of connections of a loaded single-phase alternator.

of a certain *inherent regulation* of the machine (see *A.I.E.E. Standardization Rules, Section on Regulation*).

The definition of the term "regulation," as given there, may be best explained by means of a numerical example. Suppose an alternator to be connected to the line, driven at the rated speed, and loaded to its full capacity *on a non-inductive load*, at the rated voltage, say 2200 volts. Then, let the load be thrown off and the voltage measured again at the same field current and the same speed. Suppose it to be 2330 volts; *by definition*, the regulation of the machine is

$$\frac{2330 - 2200}{2200} = 5.9 \text{ per cent.}$$

The practical meaning of the regulation is as follows: Suppose the above alternator to be running in the evening, at practically full load, on incandescent lighting, current being supplied to residences through 2200-volt to 110-volt house transformers. The lamps are burning at their rated voltage (110 volts). As time advances, lamps are gradually turned off, the load on the machine decreases and the voltage rises, unless the field current is at all times properly regulated. When only

a few lamps remain burning, the machine is running at practically no load, and the voltage would be about 2330 volts, or

$$2330 \times \frac{110}{2200} = 116.5 \text{ volts}$$

at the lamps; this is too high for 110-volt lamps, and would considerably shorten their life.

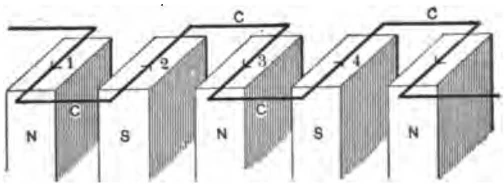

FIG. 249. Relative position of poles and armature winding when the induced e.m.f. is a maximum.

Of course, the switchboard attendant in the power house watches the voltage and regulates the field rheostat accordingly. But, since the load fluctuates constantly, it is very difficult to keep the voltage fairly constant, *if the machine has a poor inherent regulation.*

The better the desired regulation of the machine, the more expensive it is to build. For this reason, a knowledge of the factors affecting regulation becomes of great commercial importance, as well as of purely engineering interest.

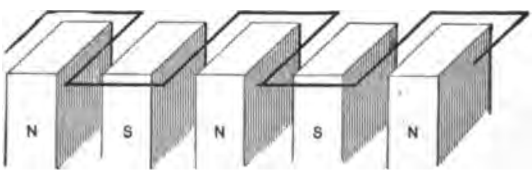

FIG. 250. Relative position of poles and armature winding when the induced e.m.f. is zero.

320. Influence of Power Factor of the Load on the Internal Voltage Drop.—Voltage drop in an alternator is considerably increased when the load is *inductive* (arc lamps, induction motors, etc.); the lower the power factor the worse being the regulation of the machine. This may be explained in two different ways:

(1) The more the current lags behind the induced e.m.f., the greater is the demagnetizing action of the armature upon the field. At a high power factor the maximum of the current wave in the armature occurs

when the armature conductors occupy the position shown in Fig. 249. The maximum of the voltage wave occurs at about the same time (at high power factors, the maximum of the current occurs when the voltage is near its maximum, and this occurs when the conductors are in the position shown). With a low power factor the maximum of the current occurs nearer the position indicated in Fig. 250, or one quarter of a period later than for unity power factor. It will be easily seen that in the second case the demagnetizing action of the armature currents is much more effective, the field of the machine is weakened more, and the terminal voltage reduced to a larger extent, than at a high power factor.

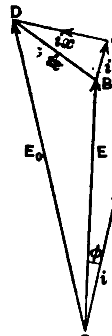

FIG. 251. Voltage drop in an alternator, at a high power factor.

(2) Another way of explaining the influence of power factor on regulation is by considering the ohmic and the inductive drop in the armature. The relations at a high power factor are shown vectorially in Fig. 251. OB is the terminal voltage of the machine; OA is the current, lagging behind it by an angle ϕ, corresponding to the power factor of the load. The ohmic drop ir in the armature is represented by the vector BC parallel to the vector of the current; the inductive drop ix by CD perpendicular to the same. The induced e.m.f. of the machine, OD, is the geometrical sum of the terminal voltage and the voltage drop in the armature. With regard to the components of the induced e.m.f. it can be said that the part DC is lost in the armature reactance, the part CB in its resistance; the rest, OB, is available at the terminals of the machine.

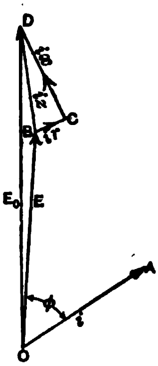

FIG. 252. Voltage drop in an alternator, at a low power factor.

Fig. 252 represents a similar diagram for the same values of induced e.m.f. and armature current, but *for a lower power factor* (angle ϕ is larger). For obvious geometrical reasons, the terminal voltage OB is lower in this case, than in Fig. 251.

In reality both factors, the demagnetizing action of the armature and the armature inductance, are present simultaneously, so that the two foregoing explanations should be combined to cover the actual phenomenon. The subject is treated more thoroughly in §§ 572 to 584.

321. Performance Curves. — As was stated above, the regulation, or the voltage drop in an alternator, depends not only upon amperes

output, but also upon the power factor of the load. For this reason the regulation of an alternator cannot be represented by one curve, as in case of a direct-current generator (Fig. 195), but requires a set of curves, as shown either in Fig. 253 or in Fig. 254. The first set gives the terminal voltage as a function of variable power factor, for constant values of the armature current. The second set of curves gives the values of terminal voltage as a function of variable armature current, for constant values of the power factor. The two sets are equivalent, and one can be plotted from the other. In taking these curves on an actual machine it is easier to keep the current constant than to maintain a constant power factor; therefore the results are usually plotted as shown in Fig. 253. Then, if desired, the ordinates of these curves can be recombined so as to obtain the curves shown in Fig. 254.

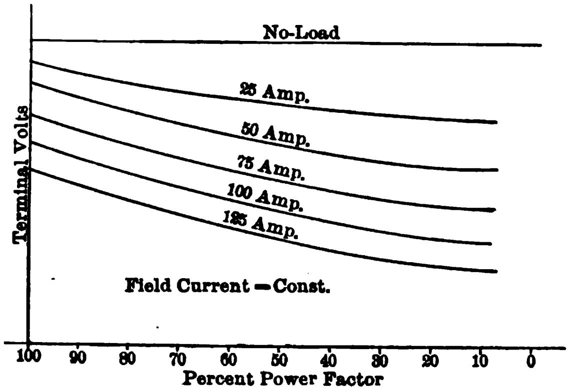

FIG. 253. Voltage characteristics of an alternator, as depending on the power-factor of the load.

322. EXPERIMENT 16-B. — Voltage Characteristics of a Loaded Alternator.— The purpose of the experiment is to obtain regulation curves (Fig. 253) showing the influence of the current, and of the power factor of the load, on the terminal voltage of an alternator. In order to facilitate the experiment, a single-phase machine should be selected. Qualitatively the same phenomena are observed in polyphase alternators, while the measurements are more complicated.

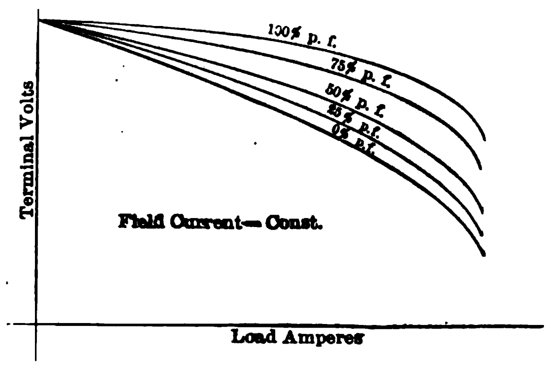

FIG. 254. Voltage characteristics of an alternator, as depending on the load current.

The connections are shown in Fig. 248; they are the same as in Fig. 247, save that a load is added, consisting of a resistance R and an impedance coil L in parallel with it. The current may be regulated separately in either branch, and read on the corresponding ammeters A_2 and A_3; the ammeter A_1 measures the total current of the machine. In reality, all three currents are usually read on the same ammeter which is connected in succession into three parts of the circuit, by means of a suitable multi-throw switch, or polyphase board (§ 49). In some cases, especially with large machines, it is convenient to use a synchronous motor as a load, with or without ohmic resistances in parallel. By regulating the field current of the motor, it may be made to take a large leading or lagging wattless component and thus vary the power factor of the load (see Chapter XXVI).

Begin the experiment by determining the value of the field current at which the machine gives its full rated (non-inductive) current at normal voltage. This field current and the speed of the machine must be kept constant while the curves shown in Fig. 253 are taken. Begin the readings with the most unfavorable conditions — lowest power factor and heaviest current (about 25 per cent overload). Keep the current constant and gradually raise the power factor to 100 per cent by reducing the inductive component of the current and increasing the current in the non-inductive resistance. This will give the lowest regulation curve. Take all the other curves in a similar manner, and finally throw off the load altogether and measure the no-load voltage (the upper horizontal line).

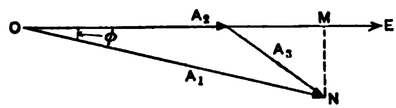

FIG. 255. Diagram of currents read on the three ammeters in Fig. 248.

For each point on the curves read volts, amperes and watts; also read separately the amperes in the non-inductive and the inductive branches of the circuit (ammeters A_2 and A_3). It will be seen that the arithmetical sum of these currents is always larger than the total current shown on the ammeter A_1, since the two currents A_2 and A_3 *are not in phase with each other;* A_1 represents their geometrical sum (Fig. 255).

The readings may be conveniently recorded on a data sheet similar to the one shown below.

Report. (1) Plot the curves shown in Fig. 253, and supplement them by a curve showing *per cent* regulation at full-load current, with different values of power factor (§ 319).

(2) Explain by means of an example how to convert these curves into the curves shown in Fig. 254.

(3) Take a few sets of readings of total and component amperes, and construct triangles, as shown in Fig. 255. From such triangles the power factor can be determined without the use of a wattmeter. See if the values of the power factor determined as the ratio of *OM* to *ON* check with those figured from the wattmeter readings.

	Load Amps. Constant at ——— Per Cent Full Load Rating.						
	Amperes.			Volts.	Watts.	Field Amps.	Speed.
	Non-Ind.	Ind.	Total.				
Inst. No.							
Const.							

323. Maintaining Constant Voltage. — In the above explanations and while performing Experiment 16-B, it is assumed that the field current is not varied, and that no attempt is made to keep the voltage constant. In actual operation, however, the terminal voltage of the machine, rather than the field current, is kept constant, and the field excitation is varied according to the load. It is of importance to know the limits within which the field current must be varied in order to keep the voltage constant (Fig. 256). The designer is interested in this in order to give proper dimensions to the field coils and to the field rheostat. The operating engineer wants to know this curve in order to be able to judge how sensitive the alternator is to changes of load, and how difficult it will be to maintain the proper voltage regulation. The curve shown in Fig. 256 is called the *excitation characteristic;* it gives the values of field amperes necessary for maintaining a constant terminal voltage with different loads. The horizontal line shows the value of field current which gives the same terminal voltage at no load.

324. EXPERIMENT 16-C. — Excitation Characteristics of an Alternator. — The connections are the same as in Experiment 16-B; similar load tests must be performed, and the same data sheet may be

used. The only difference is that now the terminal voltage is kept constant, and the field current is varied accordingly.

The regulation of an alternator depends essentially on the degree of saturation of the magnetic circuit; with highly saturated pole-pieces even a considerable number of demagnetizing ampere-turns on the armature has less effect than a smaller number with unsaturated poles. Therefore a machine with highly saturated poles gives, under equal circumstances, a better regulation, though, of course, it requires more copper on the exciting coils.

In order to see the effect of saturation, take two sets of curves, with different terminal voltages. Select one of the voltages as high as it is possible to obtain with highly inductive load, by cutting out all the resistance of the field rheostat. The other voltage must be selected considerably lower — if possible, below the knee of the saturation curve (Fig. 128). In each case begin the run with the lowest power factor obtainable. Gradually increase the power factor up to 100 per cent, keeping the current constant, and, at the same time, varying the exciting current so as to keep the terminal voltage constant. Then throw off the load and reduce the field current so as to get the same voltage again. This will give the ordinate of the horizontal line shown in Fig. 256. For each setting of the load read field amperes and watts; keep volts, armature amperes and the speed constant.

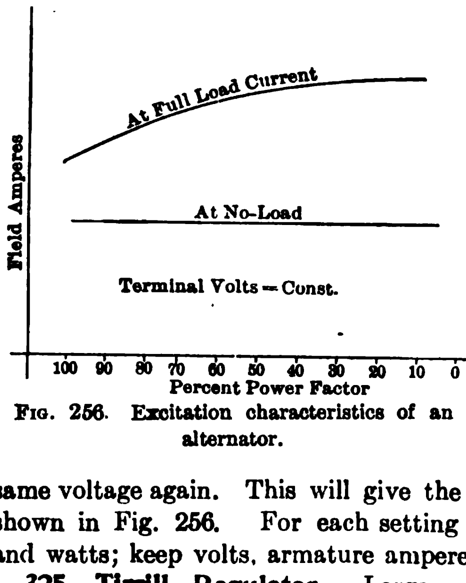

FIG. 256. Excitation characteristics of an alternator.

325. Tirrill Regulator. — Large variations of voltage common with alternators make an automatic pressure regulation highly desirable. Numerous attempts at compounding alternators have proven to be impracticable as they are too complicated.* Another solution, namely, placing an automatic regulator *outside* of the machine, proved to be more of a success. The Tirrill regulator, described in § 231 in application to direct-current generators, may be used with some modifications for maintaining constant voltage in alternators.

* For a bibliography of various methods proposed for compounding alternators see the *Bulletins de la Société Internationale des Electriciens*, Vol. IX, 1909, pp. 717 to 719.

The regulator is represented schematically in Fig. 257. As is explained in the description of the direct-current regulator, it periodically short-circuits the field rheostat of the machine, or, in this case, the field rheostat of the exciter. The relative durations of short-circuit and open circuit are made to depend on the terminal voltage of the alternator. The exciter rheostat is short-circuited between the two relay contacts, when the differential relay under the contact arm is deënergized. The deënergizing is done by the main contacts, which are closed and opened by the direct-current control magnet shown to the left. The duration of the contact is determined by the position of the right-hand lever actuated by the alternating-current control magnet.

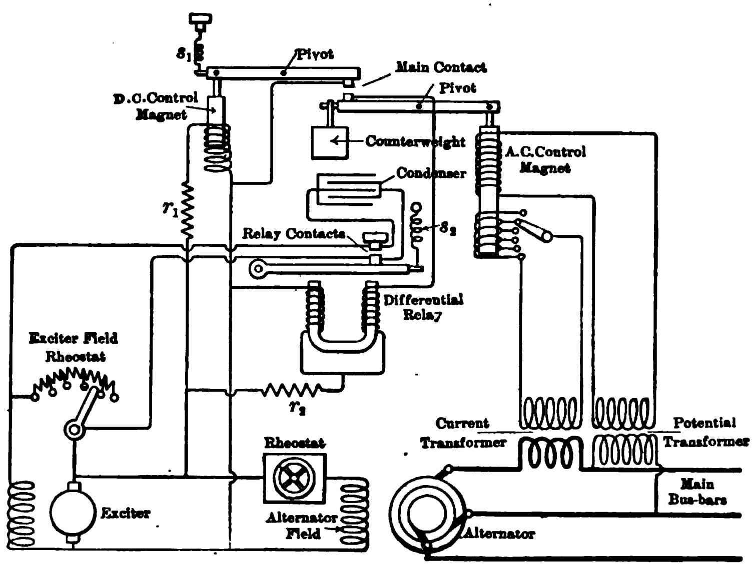

FIG. 257. Diagram of connections of the Tirrill voltage-regulator as used with an alternator.

Assuming first the main contacts to be open, only the left-hand leg of the differential relay is energized and the relay contacts are opened. This brings down the exciter voltage, and the spring s_1 closes the main contacts. A current flows through the right-hand leg of the differential relay, destroying its magnetism. Thereupon the relay contact is closed, and the exciter voltage suddenly increased. The D. C. control magnet overcomes the action of the spring s_1 and again opens the main contacts, etc. Thus, both contacts are all the time vibrating, and maintain the right exciter voltage. If the voltage on the alternating-current side should increase above normal, the A. C. control magnet

is pulled upward. This brings the main contacts farther apart, and reduces the time of short-circuit of the exciter rheostat; the voltage is thus brought back to its normal value. If the A. C. voltage should be below normal, the same solenoid brings the main contacts closer together.

If it is desired to have the alternator over-compounded — to give a higher voltage with increasing load — a series winding is provided on the A. C. control magnet connected to the main line through a series transformer. Its action is such, that when the load increases, the main contacts are brought closer together. The number of turns on this winding is adjustable for different degrees of over-compounding. The condenser shown across the relay contacts serves for suppressing sparking at these contacts. The other details of the apparatus are clearly seen in the diagram. In its general appearance the regulator is similar to the direct-current regulator, shown in Fig. 202.

326. EXPERIMENT 16-D. — Study of the Tirrill Regulator. — The regulator described in the preceding article is connected as shown in Fig. 257, and its performance observed under various conditions met with in practice. Vary the load of the machine, in turn, gradually and suddenly; vary its speed, setting of the rheostats, adjustments of springs, etc. Connect the compound winding and observe its action with various values of power factor of the load. Investigate the action of all factors separately, and report results systematically and with necessary explanations.

ALTERNATORS IN PARALLEL.

327. Two direct-current machines can be put in parallel as soon as their voltages are approximately equal (§ 234.) But before switching two alternators in parallel three conditions must be fulfilled; namely, the machines must

(1) Give the same voltage;
(2) Have the same frequency;
(3) Be *in phase* with one another.

Unless all these requirements were fulfilled, one of the machines would send part of the current into the other machine, instead of sending it to the line. Only when the e.m.f.'s of both alternators are equal *at all moments*—which means the fulfillment of the above three conditions—are their actions properly combined, and each can send its current to the line.

The process of bringing an alternator to the voltage, frequency and phase of another alternator is called *synchronizing* (the word literally means "bringing in the same time"). Let us investigate what would

occur if two alternators should be connected to the same bus-bars without all of the above-stated conditions being fulfilled.

(1) If the two machines are excited so as to give *different voltages*, the other two conditions being fulfilled, a wattless current circulates between the two machines, leading in the machine excited lower, and lagging in the machine excited higher. This has the effect of strengthening the field of the first machine and weakening the field of the second machine; the resultant voltage at the bus-bars is, therefore, somewhere between the voltages of the two machines. The set may still work satisfactorily, provided this wattless current is not too heavy, but it does not help the operation and gives an unnecessary I^2R loss in the armatures of both machines. Should this wattless current become sufficiently large, it may heat up the machines or open the main circuit-breakers, though the external load may be quite small.

(2) If the machines have *a different frequency*, the current which they supply is an *interference* current, without any definite frequency; it could not be used either for lamps or motors. To see this clearly, draw two sine waves of frequencies differing by, say, 5 per cent, one from the other, and add them together. Moreover, under such circumstances each machine would be partially short-circuited on the other; in fact, if coupling without synchronizing is attempted, the circuit-protecting devices immediately open the circuit.

(3) If the machines are *not in phase*, in other words, if the maxima of their e.m.f. waves do not occur at the same moments, a current circulates between the two machines, under a pressure equal to the difference of their e.m.f.'s, and we have again, in an exaggerated manner, the conditions described above under (1). It may also be pointed out here, that if the two machines have *different wave forms*, equalizing currents are always present to some extent, but unless the wave forms are very much different, these currents do little harm aside from causing additional heating of the machines, and lowering somewhat their efficiency.

Knowing the frequency of the supply and the number of poles of the machine to be synchronized, it is easy to determine the speed necessary for the desired frequency. If, for instance, the machine has 30 poles, it gives 30 alternations during one complete revolution; so that if the frequency of the supply is 7200 alternations per minute, the machine must revolve $7200 \div 30 = 240$ times per minute in order to give this number of alternations. The simple rule is: the speed of an alternator in r.p.m. is found by dividing the frequency of the supply (in alternations per minute), by the number of poles of the machine. For a description of direct-reading frequency indicators see §§ 555 and 556 in Vol. II.

After the right speed has been approximately obtained, the field of the alternator is so adjusted as to give about the same voltage as that of the bus-bars to which the machine is to be connected. It only remains then to bring the machine *into phase* with the voltage at the bus-bars. This is done either by means of properly connected incandescent lamps (synchronizing lamps), or special instruments, so-called synchroscopes, or synchronism indicators.

328. Synchronizing Lamps. — Synchronizing lamps are connected as shown in Fig. 258, around the main switch which connects the machine to the bus-bars. As long as the alternator is not in phase with the line, equalizing currents circulate through it, and the lamps a serve both to reduce and to indicate these currents. By varying the speed of the alternator, it is possible to extinguish the lamps; this will show that the machine is in perfect synchronism, and the switch can be closed. The sketch illustrates the case of a three-phase machine; with a single-phase machine one of the lines, say CC_1, is omitted.

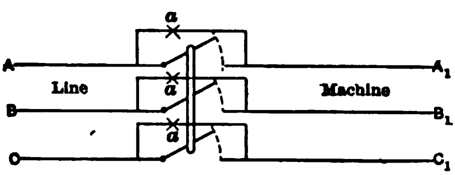

FIG. 258. Synchronizing lamps.

Some prefer to have synchronizing lamps crossed, as shown in Fig. 259. The machine is in synchronism when the lamps glow the brightest. As an advantage of this arrangement, it is claimed that should a lamp burn out during the process of synchronizing, the operator would immediately notice it, while with the first arrangement he may judge, by the lamps being extinguished, that the machines are in perfect synchronism. Thus he may close the switch while the machine is altogether out of phase, and, unless the protective devices (fuses or circuit-breakers) operate promptly, the machine may be damaged by the rush of current. However, the possibility of a synchronizing lamp burning out is rather remote, and, with two- or three-phase machines, the burning out of one set of lamps would not affect the others. On the other hand, it is generally considered that it is easier to observe moments of total extinguishing than moments of maximum brilliancy.

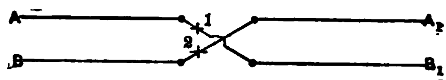

FIG. 259. Crossed synchronizing lamps.

With three-phase machines, crossing synchronizing lamps in two phases is very convenient, especially when the lamps are arranged in a

circle, as in Fig. 260. In this case, maximum brightness occurs in the three sets of the lamps in rotation, so that the light appears traveling along the circle. The direction in which the light rotates depends on whether the speed of the machine is low, or high. When the machine is in synchronism, the lamps marked "3" are dark, while the lamps "2" and "1" glow brightly.

If two 220-volt single-phase machines are to be put in parallel, at least four ordinary 110-volt synchronizing lamps should be used in series, because at certain moments during synchronizing the e.m.f.'s of the machines may be acting in the same direction instead of in opposition, thus giving 440 volts. It is even better to have, under these conditions, 5 lamps in series, so as not to let them glow too brightly; then it is easier to observe the periods of the extinguishing of the light. With two three-phase machines of the same voltage, the pressure across the lamps in each phase can never exceed 220 volts, so that two 110-volt lamps in series are sufficient, though three lamps may give a better service.

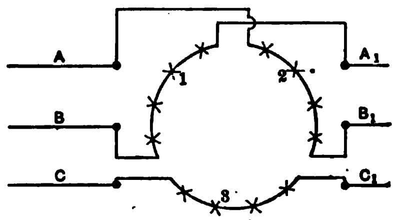

FIG. 260. Synchronizing lamps arranged in a circle.

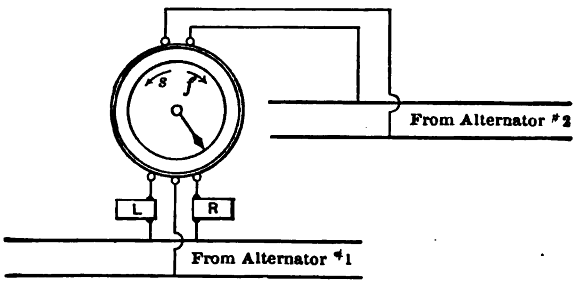

FIG. 261. Connections to a single-phase synchronism indicator.

329. Synchronism Indicators. — During the last few years, synchronizing lamps have gradually given place to special synchronizing instruments, so-called synchroscopes, or synchronism indicators. These devices have the appearance of ordinary switchboard instruments (Fig. 261), except that the pointer has no retaining spring or weight, and is free to revolve through 360 degrees. When the speed of the alternator to be synchronized is low, the pointer revolves in one direction; if it is high, it rotates in the opposite direction. When the speed is right,

the pointer stands still; and when the machine is "in phase," the pointer shows zero, indicating that the main switch may be closed.

In their construction synchronism indicators resemble small alternating-current motors. The field is connected to one of the machines, or to the line, and the armature to the machine to be synchronized

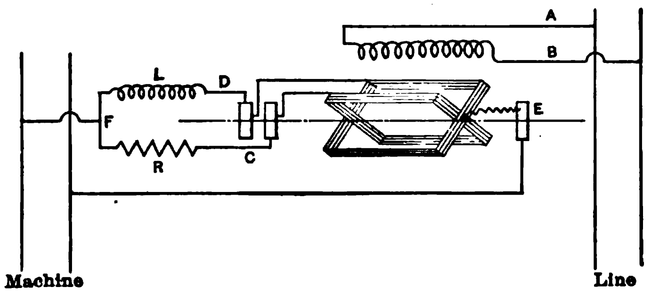

FIG. 262. The revolving armature of a General Electric synchronism indicator.

(Fig. 262). When the frequencies of the two machines are different, the resultant field in the synchronism indicator constantly changes its position, making the armature revolve in one or the other direction. When the frequency is the same, the field is stationary in space; when finally the machines are in phase with each other, the field occupies such a position that the pointer, connected to the armature, shows zero.

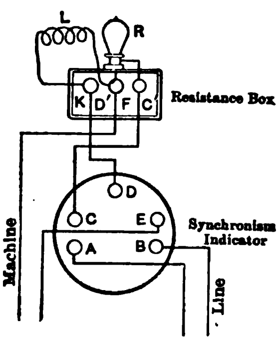

FIG. 263. The actual connections between the split-phase box and the synchronism indicator.

The synchronism indicator, illustrated in Figs. 261, 262 and 263, is adapted for use with single-phase alternators, though it may be used with polyphase alternators as well. The stationary field is connected to the bus-bars (line); the revolving armature is connected to the machine to be "thrown in," through some inductance L and resistance R, usually an incandescent lamp. The armature is of the drum type; it has two coils rigidly fastened at right angles to each other and connected in series. Their junction is connected through the collector ring E to the binding post marked E. The other two terminals are brought out, also through collector rings, to binding posts C and D (Fig. 263).

R and L are used for "splitting" the phase of the armature current, so as to produce a revolving field, as in single-phase induction motors (see § 348). The two currents in the armature coils are displaced in phase, and the coils themselves are also displaced geometrically; under these conditions the two currents produce a revolving magnetic field. A and B are the terminals of the stationary field winding of the synchroscope; it is excited from the main bus-bars.

Thus, we have in this device a stationary pulsating field produced by one machine and a revolving field (split-phase arrangement) produced by the other machine. If the frequencies of both machines are equal, there is a certain stable position of the armature of the synchronism indicator, in which position the interaction between the two fields is practically zero. If, however, the frequencies are different, one sine-wave continually changes its phase relation with respect to the other, and the position of stability of the armature also continually changes. This causes the armature to revolve at a speed equal to the difference of the frequencies.

No split-phase arrangement is used in synchroscopes which are specially built for two- or three-phase service, and all the windings are stationary; the revolving element consists merely of a light iron vane. The construction is similar to that of the power-factor meter shown in Fig. 85, except that shunt transformers are used instead of the series transformers T. One of the machines is connected to the three-phase winding W which produces a revolving magnetic flux. The coil P inside of this winding is connected to one of the phases of the other machine. The revolving flux produced by W may be considered as consisting of two pulsating components; when the machines have the same frequency, one of these components is destroyed by the action of the coil P, and the magnetic vane is held in the direction of the other component. When the machines are not in synchronism no perfect compensation is possible, and the magnetic vane revolves, following the rotating magnetic field.

330. Remarks on Synchronizing. — Some additional remarks may be useful for performing the experiment on synchronizing alternators, described below.

(1) For synchronizing high-tension alternators, the synchronizing lamps and synchronism indicators are connected through potential transformers.

(2) Ordinary voltmeters can be used for synchronizing, instead of lamps; a voltmeter can be safely connected between the machines because of its high resistance. When the machines are in synchronism, the voltmeter pointer comes to zero; otherwise it swings to and fro.

(3) In synchronizing three-phase machines, lamps must be provided in at least two phases. It is not sufficient to have the lamps in one phase only, because when A is connected to A_1 (Fig. 258), B may be connected to C_1 and C to B_1, thus causing a partial short-circuit.

(4) An automatic synchronizer is now available, with which machines can be synchronized and connected to bus bars in less time than with manual operation. This automatic synchronizer is essentially a double relay which closes the main switch of the incoming machine when the latter is in synchronism. A dash-pot on one of the parts prevents the contact from being closed too soon, and is an essential part of the mechanism. For a detailed description of the device see *The Electric Journal*, 1907, p. 490. See also Note I on p. 365.

(5) With two *direct-current* generators working in parallel, the amount of power delivered by one of the machines can be increased by increasing its field excitation (§ 234). Such is not the case with *alternators.* Increasing the excitation merely produces *wattless* currents, which tend to demagnetize the field and thus reduce its strength to the former value. The only way to increase the *output of an alternator* working in parallel with other machines is to increase the *input into the driving motor,* or the prime mover. Then the *working* component of the current is also increased.

331. EXPERIMENT 16-E. — Exercises in Synchronizing Alternators. — The experiment should be conducted as follows:

(1) Practice synchronizing a single-phase alternator, or one phase of a polyphase alternator, using it as a single-phase machine. After this has been successfully accomplished, the synchronizing of three phases may be tried. The student is warned against closing the main switch too soon; the lamps should remain extinguished several seconds at a time, in order to be sure that the machine is in synchronism and at the right speed.

(2) Synchronize with lamps crossed, as per Figs. 259 and 260.

(3) Try synchronizing with a voltmeter.

(4) Connect up and observe the operation of a synchronism indicator.

Repeat each experiment several times, and form your opinion as to how long it should take to synchronize the machine under ordinary commercial conditions, from the time it is started from rest until it is connected to the bus-bars and takes its share of load.

(5) See what effect it has on the machine if it is switched in without having the three necessary conditions fulfilled (§ 327) — the voltage of the machine not brought up to the proper value, the machine not in

phase with the supply voltage, etc. This produces a partial, or even a complete, short-circuit; hence, be sure that the machine is properly protected by a reliable circuit-breaker. Try Brooks's method of synchronizing, described on the next page.

(6) Vary the excitation of the alternator without increasing the input into the driving motor: It will be found that the current may be increased several times, while the wattmeter reading will be comparatively little affected; this will show that the increase in current is due to a wattless component. Some increase in the wattmeter reading will be, however, noticeable, due to a larger copper loss with heavier currents (see under (5) in the preceding article).

(7) After the machine has been synchronized and connected to the supply, open the main switch of the driving motor; the set will continue to rotate, the generator having evidently become a motor, driving the other machine. To make this still more evident, instead of opening the motor switch, leave the direct-current motor connected to its supply, and gradually increase its field current. The counter-e.m.f. of the motor will increase, and the current drawn from the line will diminish. When this counter-e.m.f. becomes higher than the e.m.f. of the supply, the motor begins to send current back into the circuit, thus becoming a direct-current generator. At the same time, the power generated by the alternator will diminish, and finally the wattmeter will begin to read in the opposite direction, showing that the machine now takes in some power, instead of generating it; in other words, it is acting as a *synchronous* motor.

Thus, by properly regulating the energy relations in the driving motor, the alternator can be made to operate either as a generator, or as a motor.

Report. (1) State how long it should take an experienced man to synchronize the alternator with lamps; with a voltmeter; with a synchroscope.

(2) Describe the phenomena observed when the main switch was closed without having the machine properly synchronized.

(3) Plot, to alternator field current as abscissæ, the results of the run (*b*), specified above. Plot the armature current, watts, working component of the current, its wattless component and the current input into the driving motor. Give an explanation of the curves.

(4) Plot, to the field current of the driving motor as abscissæ: currents in the armatures of both machines, volts, watts, and the efficiency of the set. In plotting watts consider the output of the alternator as positive, the input into the synchronous motor as negative; use the opposite signs for the driving motor.

NOTE I, TO PP. 363 AND 364. Prof. Morgan Brooks and Mr. M. K. Akers have proposed the use of reactance coils without iron, for a quick and safe synchronizing of alternators. According to their method, large reactance coils without iron are connected in series with the leads of the machine to be synchronized, and the machine is switched in as soon as the three conditions mentioned in § 327 are *approximately* fulfilled. The reactance coils limit the inrush of the current into the machine to a safe limit, and the wattless currents circulating through the armature pull the machine into synchronism. Then the reactance coils are short-circuited. With machines of moderate size the simplest way is to bring the machine to a speed a little above synchronous, then switch it in, and let it slow down. In doing so it is pulled into synchronism.

The reactance coils must contain no iron, because iron may have a residual magnetism in the wrong direction. This would cause a large inrush of current harmful for the other machines, or might open their circuit-breakers.

The student is advised to try this method of synchronizing alternators, first, by switching the incoming machine "in," when it is practically in synchronism; then gradually increasing the margin, so as to see the possibilities of the method and the saving in time obtained. Then the student should use reactances of the same magnitude, but with a considerable amount of iron in them, in order to see the difference in the action. Finally, ordinary resistances should be tried so that the student may see the difference in the synchronizing power. *The Self-synchronizing of Alternators*, by Morgan Brooks and M. K. Akers; Trans. of the Amer. Inst. of Electr. Engineers, 1906, p. 453.

NOTE II. For operating features of the synchronous motor see Chapter XXVI, Volume II. Commercial tests on alternators and synchronous motors are described in Chapter XXVII, Volume II.

CHAPTER XVII.

THE INDUCTION MOTOR—OPERATING FEATURES.

332. The induction motor is the most popular type of alternating-current motors, and finds a wide field of application. Its action is based on the principle of the *revolving magnetic field* produced by alternating currents displaced in phase relative to each other (polyphase currents, Chapter XXV). At least two currents of different phase are necessary in order to produce a revolving field; but for the economy and convenience of transmission of electric power (see § 538, Vol. II), it is preferable to have three alternating currents displaced in phase by

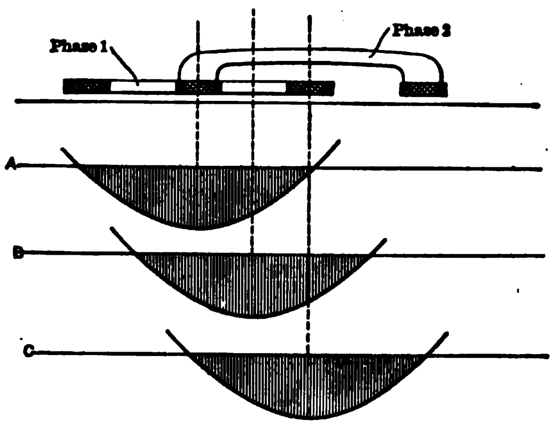

Fig. 264. The progression of a magnetic field produced by two-phase currents.

120 degrees (Figs. 395 and 396). Accordingly, induction motors are wound for two- or three-phase circuits.

Fig. 264 shows a moving magnetic field produced by two alternating currents displaced in phase. The currents in the two coils are displaced in phase by 90 *electrical* degrees, so that the current in one phase reaches its maximum when the current in the other phase passes through its zero value, and vice versa. The coils themselves are also displaced geometrically with respect to each other. When the current is at its maximum in phase 1, phase 2 is inoperative, and the magnetic field has the position denoted by A. One quarter period later the current

in phase 2 reaches its maximum, and the field occupies the position denoted by C. At an intermediate moment, when currents are flowing in both windings the field occupies an intermediate position, denoted by B. It will thus be seen that during one half of an alternation of the supply currents the magnetic field is shifted from the position A to the position C. During the next half alternation the field moves farther to the right by the same amount, etc.

This simple scheme explains how it is possible to produce a moving magnetic field with stationary windings, provided that the currents flowing through these windings are displaced in phase, and the windings themselves are displaced geometrically with respect to one another. For a detailed study of revolving magnetic field see §§ 616 to 622, Vol. II.

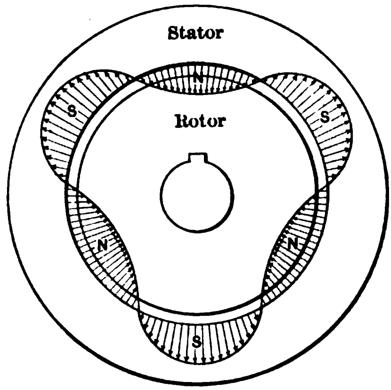

FIG. 265. The field in the air-gap of a six-pole induction motor.

333. Stator and Rotor. — Fig. 265 represents the magnetic field of a six-pole induction motor at a certain moment of time. This field, produced by the windings placed on the stationary part of the motor, or the *stator*, travels along the air-gap at a speed which depends upon the frequency of the supply currents.

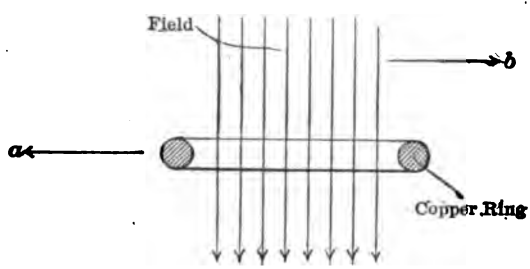

FIG. 266. Reaction between a magnetic field and a closed conductor.

The revolving part, or the *rotor*, consists of an iron core and a winding short-circuited upon itself. The revolving magnetic flux induces secondary currents in this winding, and, by its magnetic action upon the flux produced by these currents, exerts a torque which makes the rotor follow the revolving flux. This is but a modification of the famous Arago experiment in which a copper disk was made to follow a revolving permanent magnet.

The action of the revolving magnetic flux on the rotor may also be explained with reference to Fig. 266. Assuming the copper ring to be stationary and the magnetic field to be moving in the direction *b*, currents will be induced in the ring, in such a direction as to exert an attraction upon the field. The copper ring will have a tendency to follow the field, overcoming a mechanical force that may be applied to it in the direction *a*. This follows directly from the law of conservation of energy; by following the field the currents in the ring are decreased, while otherwise they would increase indefinitely.

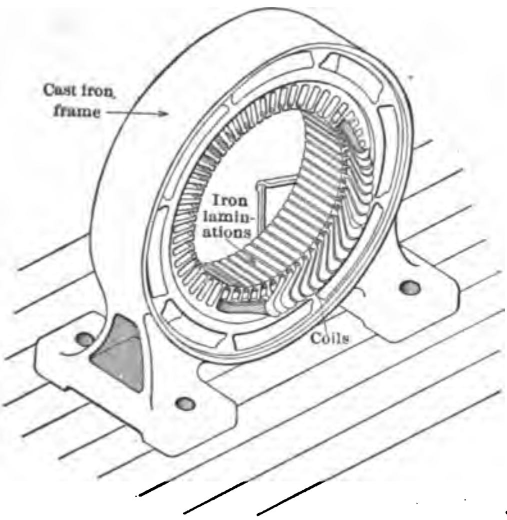

FIG. 267. The stator of an induction motor.

The stationary part, or the stator, of an induction motor is shown in Fig. 267. It consists of a laminated iron frame, held by a cast-iron housing and provided with a regular three-phase or two-phase winding, similar to that of an alternator; the winding is connected to a line, which supplies the motor with power.

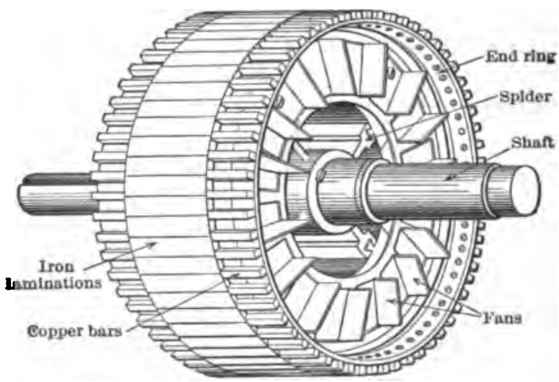

FIG. 268. The squirrel-cage rotor of an induction motor.

The rotor, or the secondary part of the motor, is shown in Fig. 268; it consists of a laminated iron core mounted on a cast-iron spider and

provided with a winding short-circuited upon itself. This particular rotor has a winding of the so-called "squirrel-cage" type, which consists of copper bars slightly insulated from the iron and connected on both ends to metallic rings which complete the circuit.

334. Slip and Torque. — The speed of the revolving magnetic field depends on the frequency of the line currents and the number of poles of the stator. During one alternation of the supply current the field travels from one pole to the next pole, therefore the number of revolutions of the rotating field per minute is equal to the number of alternations (frequency) of the system divided by the number of poles of the stator winding. For instance, on ordinary 7200 alternation lighting circuits the revolving field of a 6-pole induction motor makes $7200 \div 6 = 1200$ revolutions per minute.

The speed of the rotor is lower than that of the revolving field, in order that the lines of force may cut the secondary conductors. In practice, the speed of the armature at full load is a few per cent less than that of the revolving field; for instance, the actual speed of the above-mentioned motor would be somewhere near 1140 r.p.m. This difference in speed is called *the slip* of the induction motor, and is usually measured in per cent of the speed of the revolving field, which latter speed is also called the *synchronous speed.* Thus the synchronous speed of the above motor is 1200 r.p.m. and the slip at full load is

$$\frac{1200 - 1140}{1200} = 5 \text{ per cent.}$$

The slip depends on the load of the motor and increases with it. At no load the motor runs almost synchronously, because a very small difference of speed between the revolving field and the rotor is sufficient to induce currents in the latter, furnishing the torque necessary for overcoming the friction and windage. As the load increases, the slip also increases, the rotor runs more slowly, and the induced currents become larger; in consequence, the torque on the motor is increased, as it ought to be. When the load exceeds a certain limit, the motor "pulls out" and comes to a stop. The overload capacity of an induction motor is usually measured by the ratio

$$\frac{\textit{pull-out torque}}{\textit{full-load torque}}.$$

This ratio varies from 1.3 to 2.5 and higher, according to the size and type of the motor and the purpose for which it is designed.

335. Starting Devices. — Induction motors cannot be started by simply switching them on to the line (except in very small sizes), because the rush of current during the first moments would be too large. The

starting is done at a voltage considerably lower than that of the line, and then, as the motor gains in speed, the voltage is increased in a few steps to that of the line. The gradations of the voltage are obtained by means of two V-connected auto-transformers with several taps (Fig. 269); a controller or switch is provided, usually immersed in oil, for safety and durability. The transformers and the switch are inclosed in a common case, and the apparatus is called an "auto-starter" or "compensator" (Fig. 270).

The auto-starter connections are such that at starting, the transformers are connected to the line, while the motor windings are connected across a certain part of the transformer windings, giving a lower voltage. After the motor has reached a considerable speed, the switch is turned to the "running" position, in which the auto-transformers are entirely disconnected from the line and the motor is directly connected to the line.

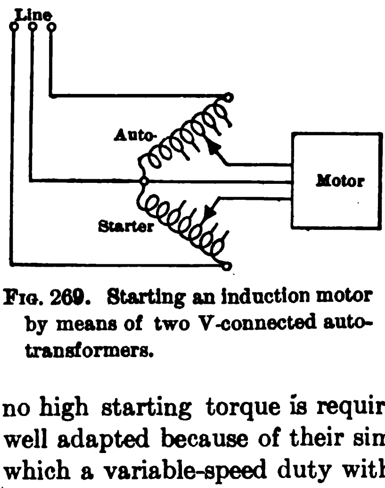

FIG. 269. Starting an induction motor by means of two V-connected auto-transformers.

An induction motor with a squirrel-cage secondary is essentially a constant-speed motor, as the difference in speed between no load and full load is but a few per cent. The starting torque of this type of motors is not particularly high, the motor being started on a low voltage.* For driving machine shops and similar purposes, where no high starting torque is required, squirrel-cage induction motors are well adapted because of their simplicity. There are cases, however, in which a variable-speed duty with high starting torque is required, as, for instance, in crane, hoisting and similar work, for which direct-current series-wound motors are otherwise used. For such service the rotor of the induction motor is made phase-wound, with the same number of poles as the stator. The ends of the winding are connected to three slip-rings, whence connections are made to a three-phase variable rheostat. At starting, the rheostat is all connected into the circuit and the motor started at the full line voltage, with a powerful torque equal to several times full-load torque. Then the rheostat is gradually cut out and if

* According to the general theory of induction motors, the torque decreases as the square of the voltage. For torque is proportional to the product — flux times secondary current. But secondary current, being induced by the flux, is proportional to it. Therefore, torque is proportional to the square of the flux. Now, the flux is proportional to the counter-e.m.f., or, roughly, to the applied voltage. Therefore, torque is proportional to the square of the applied voltage.

necessary used for speed regulation: the more resistance is inserted into the circuit, the lower is the speed of the motor.

336. EXPERIMENT 17-A. — Exercises in Starting and Speed Control of Induction Motors. — The experiment is intended to familiarize the student with the two above-described methods of starting induction motors. If a motor is available which has a phase-wound secondary with slip rings, it is well to perform this experiment on such a motor in order to be able to compare both methods of starting. Wire up the motor so as to be able to use at will either an auto-starter or a resistance in the secondary.

(1) Compare the two methods of starting with regard to the magnitude of the current which is necessary for starting the motor at a certain load. Put on a load, say by means of a Prony brake, and start the motor, *first*, by switching the motor on the full line voltage, but having a high resistance in the secondary, the resistance being gradually cut out as the motor gains speed; *secondly*, by the usual method, with the secondary winding short-circuited, and the primary voltage reduced by means of an auto-starter.*

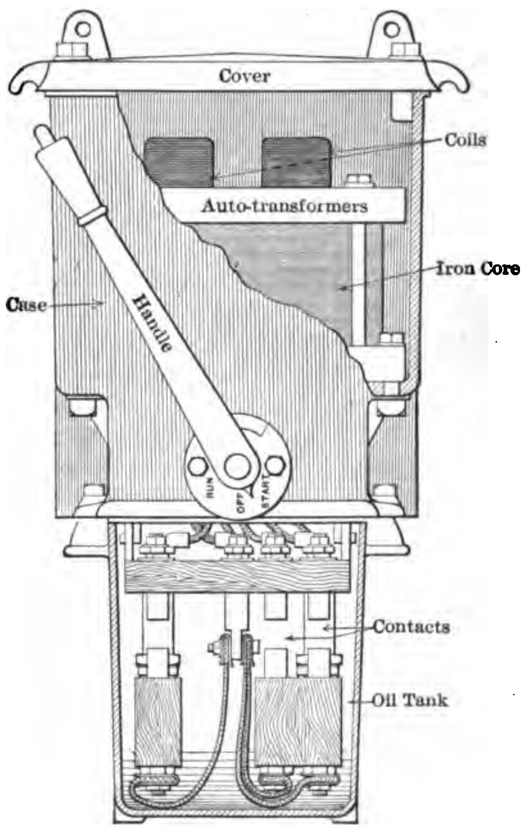

FIG. 270. An induction-motor starter.

The starting current depends on the amount of resistance inserted into the secondary, and on the starting voltage, if an auto-starter is used. Therefore, for a fair comparison, the best starting secondary re-

* The starting torque is different in different positions of the secondary relative to the primary winding. In order to have comparable results the motor must in all cases be started from the same position.

sistance and the lowest possible starting voltage must first be found. This can be done, for instance, for the full-load torque. Knowing the rated horse-power of the motor and its normal speed, the full-load torque can be easily calculated and the brake adjusted for this torque. Then a high resistance is introduced into the secondary, and is gradually cut out, until the motor starts. This is assumed to be the right value of the starting resistance for the first step of the starting rheostat. In a similar way, different taps on the transformers of the auto-starter are tried, until a voltage is found at which the motor starts with the same brake load. This is taken as the right tap for the first notch of the auto-starter.

Having thus found the proper setting of the starting apparatus for both methods of starting, start the motor at a few different values of starting torque, using both methods of starting in succession Try to read the first rush of the current and its subsequent variation as closely as possible; also note the number of seconds that it takes for the motor to attain full speed. Do this with the purpose of forming a judgment concerning the relative advantages of both methods of starting. It will be noted that leaving some resistance in the secondary circuit may considerably improve the starting torque, when the auto-starter is used, though this will somewhat lower the efficiency and increase the slip at full speed.

In making the above comparison, it must, of course, be kept in mind that a squirrel-cage motor is a less expensive and simpler machine than one with a phase-wound rotor; also that starting by means of auto-transformers is simpler and more reliable than by means of a three-phase rheostat in the secondary. Therefore the former method of starting should be invariably used where a high starting torque is not required and a large starting current is not objectionable.

(2) After this, the motor with the phase-wound secondary should be tested with regard to its speed control. Bring the motor up to its full speed by gradually short-circuiting the secondary rheostat, and put on approximately full load. Now keep the torque (not horse-power) constant, and gradually reduce the speed by again introducing resistance into the secondary. This corresponds to a practical case when a certain weight is lifted by a crane at varying speeds. Read amperes primary and secondary and the corresponding speeds with different values of secondary resistance.

Speed control by varying the primary voltage is never used, because decreasing the applied voltage rapidly reduces the magnetic flux and consequently the torque of the motor. If time permits, try this method of control, by connecting the starting resistance into the primary,

instead of the secondary circuit, and observe the behavior of the motor. The same can be done by using the several starting positions of the compensator, if it is large enough to carry the current for a considerable time.

Report. Arrange the data in the form of curves, or a table, showing the comparative behavior of the motor with the two methods of starting; show, in particular, the amount of starting current and the time that it takes to bring the motor up to speed. In regard to speed control, give curves showing the speed of the motor and the current input, as a function of the amount of resistance in the secondary circuit.

PERFORMANCE TESTS.

337. The operating features of an induction motor can be best judged from a set of curves, such as shown in Fig. 271. All the data are plotted to horse-power output as abscissæ. Some prefer to plot them to amperes, or watts input, others to pounds torque. There is not much difference between these three methods; one justification for plotting it to horse-power is that such curves are better understood by non-electrical engineers. The three most important curves are those of efficiency, power factor, and speed. The other curves may also be useful for various purposes, and are usually included on the curve-sheet. The curve marked "true H.P. Input" is obtained by dividing watts input into the motor by 746. Similarly, the ordinates of the "Apparent H.P. Input" curve represent the volt-ampere input divided by 746. The ordinates of the efficiency curve are equal to the ratios of the ordinates of the output and the true input curves. The ordinates of the power factor curve represent the ratio of true input to apparent input. In addition to these curves an "Apparent Efficiency" curve is sometimes plotted, giving the ratio of the output to apparent input.

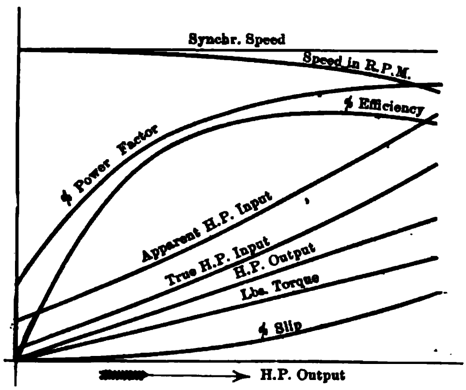

FIG. 271. Performance curves of an induction motor.

The above performance curves may be obtained from a direct brake test, or they can be calculated from the losses in the motor; sometimes they are predetermined from a vector diagram. The first two methods are described in this chapter; for the third method see Chap. XXIX in

Vol. II. The general arrangement of the brake test is the same as is described in §§ 2!_ to 255, in application to direct-current motors.

338. Measuring Input. — The electrical power-input to a three-phase motor is measured by the so-called two-wattmeter method, shown in Fig. 272. One of the line wires, say B, is assumed to be a common return wire for two other wires. The power is measured between the wires A and B, and then between C and B, and the wattmeter readings are added together in order to get the total input into the motor. Accordingly, the series winding of one wattmeter is connected into the line A, and its shunt winding across $A-B$. The series winding of the other wattmeter is connected into the line C, and the potential winding across $C-B$. With the use of a polyphase board (§ 49) only one wattmeter is needed; it is connected in succession in two positions shown in Fig. 272, and the readings added together.

Theory and experience show that this method gives correct results for the total power input on balanced as well as on unbalanced loads. However, the two component readings are equal only when the load is balanced and non-inductive (power factor of 100 per cent). With an induction motor the load is practically balanced in the three phases, but the power factor is always less than 100 per cent. Accordingly, one of the wattmeter readings is always smaller than the other. On light loads, when the power factor of an induction motor becomes less than 50 per cent, one of the wattmeters begins to give negative deflections. In this case reverse the potential or the series leads of the meter, and take the *difference* of the two readings instead of their sum.

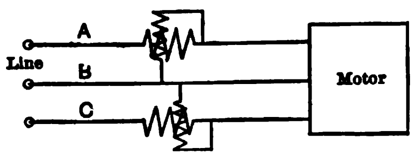

FIG. 272. Measuring power input into a three-phase motor by the two-wattmeter method.

For this reason it is advisable to begin the test at the maximum load (say 25 per cent overload) where the power factor is surely higher than 50 per cent, and then reduce the load by steps to zero. Then one cannot miss the point at which it becomes necessary to reverse the leads of one of the wattmeters. For further details in regard to the two-wattmeter method, see §§ 525 to 527. If a polyphase wattmeter is available, total power is obtained from one reading.

It would hardly be practicable to provide separate ammeters and voltmeters for each phase; a special "polyphase board" is used by means of which the same instruments may be connected in succession in the three phases. Any of the polyphase boards described in § 49 can be used for the purpose.

339. Measuring Frequency and Speed. — Measuring the speed of an induction motor deserves special attention. The speed depends on the load and on the frequency of the supply currents, as the latter determine the speed of the revolving field. If the power for testing is taken from a commercial supply, the frequency may at times be several per cent above or below the normal, and unless the exact frequency is known at the time when the speed is taken, the speed determination is of little value.

When the generator is accessible, its speed may be measured simultaneously with that of the motor, so that the two speeds refer to the same frequency. If the generator is not accessible, a small synchronous motor may be run from the same line to which the induction motor is connected. As the speed of the synchronous motor is always equal to that of the generator and automatically follows the variations in speed of the latter, the synchronous motor will give at any moment the actual speed of the generator. Special instruments, so-called frequency meters (see § 555), may also be used for measuring the frequency of the supply.

Instead of measuring the speed of the motor and the frequency of the supply, it is much preferable to measure simultaneously the speed and the slip (§ 334) of the induction motor; their sum gives the synchronous speed, and consequently the frequency of the supplied currents. If, for instance, the motor speed is 702 r.p.m., and the slip 22 r.p.m., the synchronous speed is 724 r.p.m. If the motor is a 10-pole machine, the frequency of the supply is at that particular moment 7240 alternations per minute, instead of the standard 7200. In plotting the speed curve, the corresponding correction must be made.

Slip usually constitutes but a few per cent of speed; at the same time an accurate knowledge of its value is of considerable importance to the designer as well as to the user of the motor. When slip is determined as a difference between the synchronous speed and the actual speed of the motor, a small error in the determination of either may lead to considerable error in the value of the slip figured out as the difference of the two. For this reason it is preferable to measure slip and speed directly and independently of each other, and to determine the frequency of the supply as the sum of the two. This leads us to the description of slipmeters.

340. Stroboscopic Slipmeters. — The name "stroboscopic" is usually applied to devices based on the peculiarity of our eye to preserve a continuous impression when the frequency of flickering of the light exceeds a certain limit.

(*a*) *Sectored-Disk Slipmeter.* A simple slipmeter based on this

principle is shown in Fig. 273: A pasteboard or sheet-metal disk with white sectors painted on it is mounted on the shaft of the motor. The number of sectors should be equal to the number of poles of the motor. An alternating-current arc lamp, fed from the same supply as the motor, is placed before the disk. If the motor could revolve synchronously the white sectors would appear stationary; as, however, the speed of the rotor is a few per cent below synchronism, the sectors appear to the eye slowly rotating in the direction opposite to that of the shaft.

The reason for this phenomenon is that the light of the alternating-current arc lamp is actually extinguished once during each alternation of the current. With synchronous rotation of the disk, each sector has just enough time during one alternation to occupy the position of the preceding sector. Thus, when the lamp relights, the eye of the observer finds the sectors in seemingly the same position in space, as before. The flickerings of the light occurring several thousand times per minute, the phenomenon appears as continuous. When, however, the rotor lags behind synchronism, the sectors have not enough time to move through one polar division during one alternation of the current, so that when the lamp lights up the next time, the eye finds the sector in a slightly different position. This lagging behind is going on continually, and the sectors appear to the eye slowly moving backward, while in reality they are revolving at a high speed in the direction of rotation of the shaft.

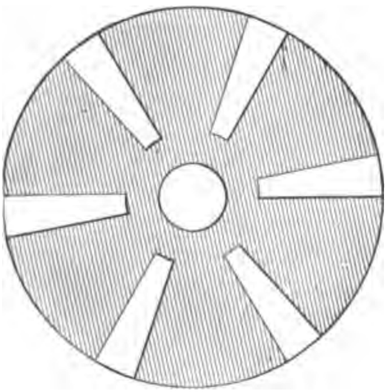

FIG. 273. Disk with painted white sectors, for measuring slip of induction motors.

The higher the slip of the motor, the faster are the sectors moving through the field of vision; the number of the *apparent* revolutions of the disk is a direct measure for the slip. In order to count the sectors more conveniently, it is advisable to limit the field of vision so as to see only one sector at a time. Suppose, for instance, that 120 sectors have passed through the field of vision in one minute, while the speed of the motor, as measured by an ordinary speed-counter, was 1765 r.p.m.; let the motor be a four-pole, 60-cycle machine. With these data the slip of the motor and the actual frequency of the supply is figured out as follows:

With 120 sectors passing through the field of vision during one minute, the motor skipped 120 alternations of the supply. As the motor has four poles it took $120 \div 4 = 30$ slip revolutions to skip 120 alternations. Hence, the synchronous speed of the motor was $1765 + 30 = 1795$ r.p.m., and the slip amounts to

$$\frac{30}{1795} = 1.67 \text{ per cent.}$$

The frequency of the supply when the speed was measured was equal to $1795 \times 4 = 7180$ alternations per minute instead of the standard frequency 7200.

It will be seen from the above example that the stroboscopic slip-

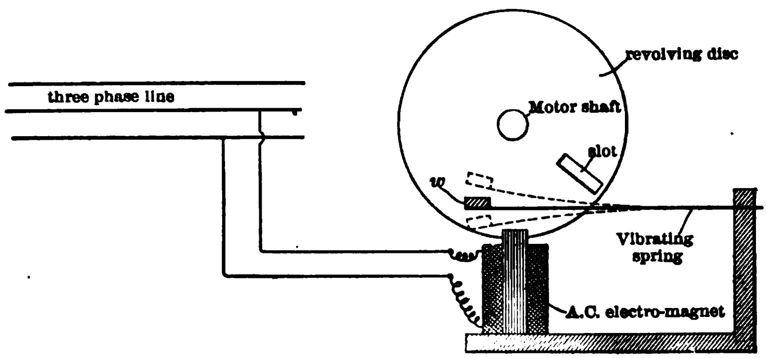

FIG. 274. A vibrating-reed slipmeter.

meter is more suitable for 25-cycle motors and for light loads than for high-frequency motors and for heavy loads, because in the latter case the sectors pass too rapidly through the field of vision, and it is difficult to count them.

(b) *Vibrating-Reed Slipmeter.* Another stroboscopic slipmeter, which does not require an arc lamp, was suggested by Professor Perkins of the University of Tennessee. It consists of an alternating-current electromagnet (Fig. 274) connected to the source of supply and provided with a steel reed near one of its ends. Alternating current flowing through the electromagnet sets the reed into synchronous vibrations. The reed is loaded at its extremity with the weight w, so as to make its natural period of vibration correspond to that of the supply. A disk with a slot in it is mounted on the shaft of the motor, and the vibrating reed is viewed through this slot. If the rotor were revolving synchronously, the reed would appear to the eye stationary, because it would be viewed by the observer always during the same part of its

vibration. As, however, the rotor lags behind synchronism the reed appears slowly moving up and down. The number of strokes per minute is proportional to the slip, as in the case of the arc-lamp slip-meter.

The reed may vibrate at a frequency some multiple of that of the supply, and it is safer to calibrate this instrument experimentally, by measuring the slip of a motor by some other method. This will give a constant by which to multiply the number of strokes in order to find the number of alternations skipped per minute.

341. Commutator Slipmeters. — In places where many induction motors are tested regularly, it is desirable to have more convenient

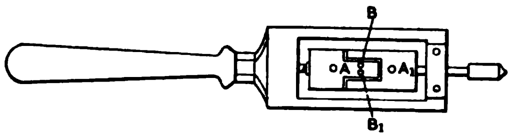

FIG. 275. A commutator-type slipmeter.

devices for measuring slip than the above-described stroboscopic slip-meters. A device of this kind is shown in Figs. 275 and 276. In its principle it is a commutator with as many segments, as the motor has poles. This commutator is pressed against the end of the motor shaft, as an ordinary speed-counter, and at the same time is connected through a resistance to the power supply and to a sensitive ammeter. If the speed of the motor were exactly synchronous, the impulses of the current, sent through the commutator into the ammeter, would be always at the same point in the alternating e.m.f. wave, and its indication would be steady. As, however, the motor *lags* behind the revolving field, these impulses occur now at the maximum of the wave, now at the intermediate values, and the needle of the ammeter swings at a speed equal to the *difference* of the speeds of the revolving field and the rotor, and hence proportional to the slip of the motor. If the slip is not too high, the number of swings per minute can be easily counted and the slip calculated. An alternating-current bell (polarized bell) can be used instead of an ammeter, and the number of strokes per minute counted.

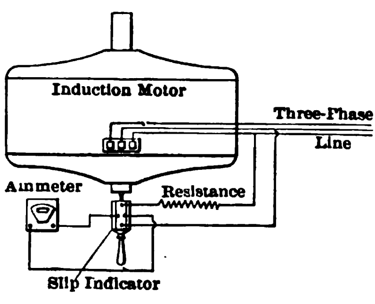

FIG. 276. Electrical connections to the slipmeter shown in Fig. 275.

The difficulty in counting the number of impulses, when the frequency is high and slip is considerable, is the same with this device as with the stroboscopic slipmeters. The Bianchi slipmeter (Fig. 277), while similar in its principle to that shown in Fig. 275, has an attachment for automatically registering the number of revolutions of slip. The impulses produced by the revolving commutator D, instead of being counted by the observer, are sent through the electromagnet M, which actuates a ratchet-and-pawl recording mechanism q, through the permanent magnet c. The number of revolutions of slip is thus recorded on the dial Z_2; at the same time the number of revolutions of the rotor

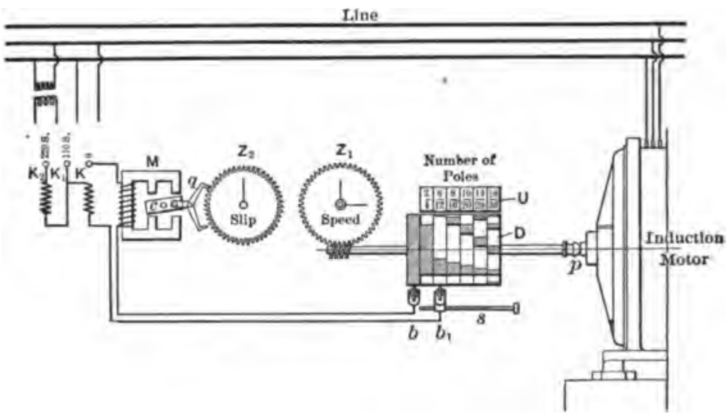

Fig. 277. The Bianchi automatic slipmeter.

is shown on the dial Z_1, connected to an ordinary speed-counter. The operation of this device is entirely automatic; it is pressed against the shaft of the motor at p, as an ordinary speed-counter, and is held for, say, one minute. The reading on one scale Z_1 gives the actual speed of the motor; the reading of the other scale gives the number of revolutions of slip; adding the two gives the synchronous speed of the motor, and consequently the frequency of the supply.

The slipmeter is connected to the line either between the terminals K and K_1, or K and K_2, according to the voltage of the motor. For higher voltages a shunt-transformer is used. The drum D is provided with different combinations of contacts, to make possible the use of the device with motors of various numbers of poles. The setting is accomplished by the screw s, which moves the roller brush b_1. The number of poles is indicated on the scale U.

Date .... Section .....

Observers:

....

....

....

....

Length of Brake Arm ....

Tare or Zero Brake Reading ....

Make of Motor ....

Type — Open, semi-enclosed, enclosed, ventilated frame { Yes. / No.

Volts .... Amps. per terminal ....

H.P. .... Mfrs' No. .... No. of Poles ....

Speed { At full load .... / At no load .... Alts. .... Cycles .....

Phase .... Connections Y or Δ.

Type of Rotor { Phase wound. / Squirrel Cage. Fans { Yes. / No.

Method of Starting ....

	Amperes.			Volts.			Watts.		Speed.		Slip indic.	Torque.
	A	B	C	AB	BC	CA	A — AB	C — CB	Motor.	Synchr.		Lbs.
Inst. No.												
Const.												

342. EXPERIMENT 17-B. — Brake Test on an Induction Motor. — The purpose of the experiment is to obtain performance curves of an induction motor, as shown in Fig. 271. Wire up the motor as per §§ 335 and 338, and let it run light for about 30 minutes to warm up the bearings. Then load the motor to about 25 per cent above its rated capacity, and, keeping the brake load as steady as possible, read volts, amperes, watts, pounds brake load, speed and slip. Reduce the load by approximately equal steps to zero, taking at each point the same readings as above. The form of data sheet shown on the opposite page will be found convenient for recording the readings.

For various methods for measuring slip see §§ 339 to 341.

Report. Give a diagram of connections used, and plot curves, as per Fig. 271. For one point on the curves give the methods and numerical calculations by which the ordinates were obtained. In figuring out results it is advisable first to multiply the torque (in foot-pounds) by the speed and divide by 5252; this will give horse power for abscissæ. Watts and volt-amperes, divided by 746, give true and apparent horse power input. True efficiency, apparent efficiency and power-factor curves are obtained as the ratios of the ordinates of the curves of output and input. Speed, slip and torque are plotted directly from the test data.

343. Load Test without Brake. — The principal difficulty in performing an accurate brake test on an induction motor is to hold the load constant while the speed and the slip are measured. Moreover, the load must be exactly the same when watts and amperes are read in the three phases. For these reasons it is preferable, in some cases, especially with large motors, to use a steadier load than is possible with a Prony brake. An electric generator, a blower, or a centrifugal pump, is particularly convenient for the purpose. Provision must be made for varying this load at will. The test is conducted similarly to a brake test, except that the output is not determined experimentally, but is calculated afterwards from the input and the losses. The latter are partly independent of the load, partly vary according to simple laws and can be calculated as is explained in the next article.

Experience shows that with this method more accurate results are obtained than with an ordinary brake test. One reason is that the speed and the load are easily maintained constant for any length of time, so that the input can be read quite accurately. Another reason is that all the readings and calculations are purely electrical, the mechanical torque being calculated from the input, instead of being read on the brake.

344. Losses in the Induction Motor. — The performance test described in the preceding article involves figuring out losses in the induc-

tion motor. These losses consist of copper loss in the primary and in the secondary windings, and of no-load losses (iron loss and friction). The latter can be assumed practically constant at all loads and having the same value as at no load (hence the name "no-load losses"). The primary copper loss can be easily calculated if the primary current and the resistance of the primary winding are known. The secondary copper loss is proportional to the per cent slip, as is shown below.

Suppose first the resistance of the secondary winding to be zero; the slip would be practically zero at any load because the secondary currents necessary for producing a torque could be induced with an infiintesimal difference in speed between the revolving flux and the rotor. If, however, the secondary winding has an appreciable resistance, a certain finite difference in speed is required in order to induce the same torque-producing currents. Thus, the necessary torque is obtained at a sacrifice of a certain per cent of speed. The corresponding loss of output is converted into the I^2R heat in the secondary winding.

The details of calculation of the output of the motor from its input and the losses may be best shown in a numerical example. A 10 horse-power, 440-volt, 3-phase induction motor was found to take 800 watts at no load; the no-load current was 5.5 amperes per phase, primary resistance 0.75 ohm per phase. From this data, iron loss and friction should first be computed; these are equal to 800 watts less a correction for the copper losses in the primary and the secondary windings. But the secondary copper loss is negligible at no load, because the slip is very small. Thus the correction amounts to $3 \times \overline{5.5}^2 \times .75 = 68$ watts, and the losses in question are equal to

$$800 - 68 = 732 \text{ watts.}$$

Take now a point on the load curve, for instance, corresponding to an input of 15 amperes per phase. Suppose that the power reading at this input was 9920 watts, and the slip 5.4 per cent. The primary copper loss is

$$3 \times \overline{15}^2 \times 0.75 = 506 \text{ watts,}$$

therefore

$$\text{Output} + \text{Sec. copper loss} = 9920 - (506 + 732) = 8682 \text{ watts,}$$

the last number representing the input into the secondary.

The secondary copper loss constitutes a part of the input into the secondary, proportional to per cent slip. Thus, in our case,

$$\text{Sec. copper loss} = 8682 \frac{5.4}{100} = 469 \text{ watts.}$$

Therefore

$$\text{Output} = 8682 - 469 = 8213 \text{ watts} = 11 \text{ horse-power.}$$

Having thus determined the output corresponding to a given input, the efficiency, the torque, etc., may be figured out as in the brake test before.

NOTE. It is not quite correct to subtract both iron loss and friction from the primary input. Most of the iron loss takes place in the primary, while the friction reduces the secondary output. The correct way would be to subtract the primary copper loss and the iron loss from the input into the primary; the result will represent the input into the secondary. The same being reduced by per cent slip represents the power developed on the shaft of the motor; subtracting the friction from it the power is obtained actually available for useful work. This accurate procedure is never used in practical testing, because there is no very simple method for separating iron loss from friction in an induction motor. The error committed is, however, so small, as to be negligible for practical purposes.

345. EXPERIMENT 17-C. — Performance of an Induction Motor from Losses. — The motor is belted to a generator, or a blower, serving as a load, and a series of readings are taken as explained in § 342, except that the brake readings are omitted. At the end of the load test, careful readings should be taken of amperes and watts at no load, and the resistances of the primary windings determined. Measure (by thermometers) the temperature of the windings while measuring their resistance.

Report. The same curves should be plotted as in the report in § 342, the results to be derived by the method described in article 344. In figuring out the primary copper loss, use the value of the primary resistance, which it has at a temperature 50 degrees C. above the temperature of the room.

It should be borne in mind that when a resistance is measured between two terminals of a Y-connected induction motor, the result thus obtained represents the double resistance per phase. Therefore, in order to obtain the *average* resistance per phase, take the resistances between the terminals $A-B$, $A-C$, and $B-C$, add them together, and divide the result by six.

Plot on a separate sheet, curves of total losses, primary and secondary I^2R losses, and iron loss + friction, against horse-power output as abscissæ, so as to have a clear expression of the relative importance of these losses at various loads.

A modification of the above test is possible when a carefully calibrated generator or an accurate transmission dynamometer, such as the one

described in § 254, is available as a load. No wattmeter readings are necessary in this case, and the input can be figured out from the output and the losses. If wattmeter readings are taken, they may be used as a check on the results. It is evident that such a check is always possible with the ordinary brake test, since the input can be figured out from the brake readings and the losses, as well as read directly on the wattmeter. Such a check is always desirable when the test is of particular importance.

SINGLE-PHASE INDUCTION MOTORS.

346. It is a well-known fact that when a two-phase or a three-phase induction motor is running, and the connection between one of the phases and the line is broken, the motor continues to run, provided the load is not too heavy. In this case it is said to operate as a single-phase motor. The motor will not start, however (without special devices), when connected to but one phase of the supply. Induction motors wound single-phase are used to some extent in places where most of the load consists of lighting, and where, therefore, power distribution is effected by single-phase lines. Such motors require special devices for starting; some of these are described below.

347. Action of Single-Phase Induction Motors. — The theory of single-phase induction motors is much more complicated than that of polyphase motors, because the currents and the fluxes in the former have rather an irregular and complicated form. The following simple explanation of the action of a single-phase induction motor is given without any claim to its absolute accuracy.

A single-phase stator winding can produce but a pulsating magnetic flux, and not a revolving one. Thus, when the motor is at rest, the rotor acts as the secondary of a transformer, and there is no reason why the motor should start in either direction. From a well-known mechanical law, the pulsating magnetic flux may be resolved into two fluxes revolving in the opposite directions. These two revolving fluxes produce equal actions on the secondary, and the actions are mutually destroyed.

But when the motor has been brought up to a certain speed by external means, the *relative* speed between one of the imaginary revolving fluxes and the rotor is decreased, while the other is increased. The dissymmetry produced is of such a nature as to give preponderance to the magnetic flux revolving in the same direction with the armature. The flux revolving in the opposite direction produces high-frequency secondary currents which are considerably out of phase with the flux, and therefore give only a small torque, which slightly reduces the useful torque of the motor.

For the theory of single-phase induction motors see Dr. McAllister's *Alternating Current Motors* and B. A. Behrend's *Induction Motor*. A good article on the subject, by Prof. Goerges, will be found in *Elektrotechnische Zeitschrift*, 1903, No. 15. See also § 621.

348. Starting with an Auxiliary Phase. — A revolving field is necessary in order to make an induction motor self-starting. This field may be produced by adding a second phase-winding to the main stator winding of the single-phase motor (Fig. 278). It is shown in § 332 that two windings, displaced relatively to each other, produce a revolving field, only when the currents flowing in these windings are out of phase with each other. In the case of the single-phase motor both windings are of necessity connected to the same phase of the supply, so that, if the circuits of the two windings were identical, the currents flowing through them would be in phase with one another, and no revolving field would be produced.

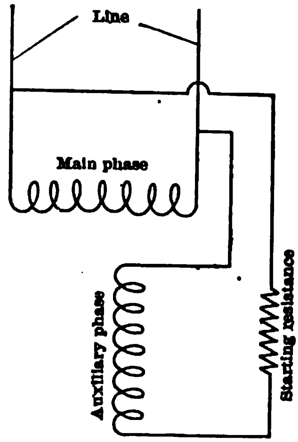

FIG. 278. Connections for starting a single-phase induction motor by means of an auxiliary phase.

In order to shift or "split" the phase of the current in one of the windings, some resistance, inductance or capacity is connected in its circuit: This makes the phase displacement either larger or smaller than in the other phase, and a revolving field is produced. When the motor is started and a considerable speed is reached, the circuit of the auxiliary phase is opened, either automatically, or by hand, and the motor continues to run single-phase. To reverse the motor, the connections to either the main or the auxiliary phase are reversed.

A special case of single-phase motors is that of fan motors in which the auxiliary phase is produced by copper rings permanently short-circuited upon themselves, — so-called "shading coils" (Fig. 43). The principle shown there in application to a measuring instrument is also used in single-phase induction motors. Very small motors may also be started without any auxiliary phase, by simply giving an energetic pull on the belt.

The revolving field produced by means of an auxiliary phase is a rather imperfect "elliptical" field at the best, and no appreciable starting torque can be expected from single-phase induction motors. The

motors are often supplied with friction clutches which are engaged only after the motor has reached a considerable speed. This is usually done automatically, by a clutch operating on the principle of centrifugal force. A small starting torque may be obtained, if desired, at the expense of an excessive starting current.

349. Three-Phase Motors on Single-Phase Circuits. — There are cases in which it becomes desirable or necessary to operate three-phase induction motors on single-phase circuits, for instance when one of the line wires or a transformer is put out of commission. A good starting arrangement is shown in Fig. 279. Two of the phase windings,

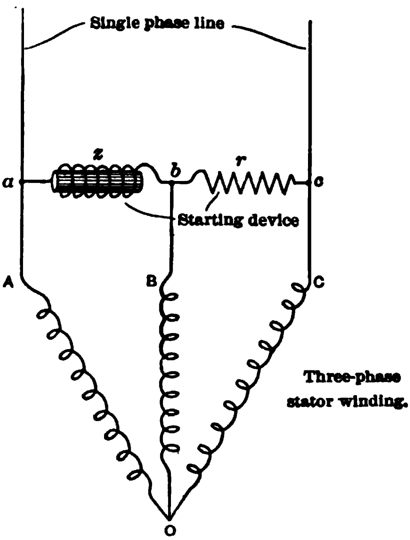

FIG. 279. Starting a three-phase induction motor on a single-phase circuit.

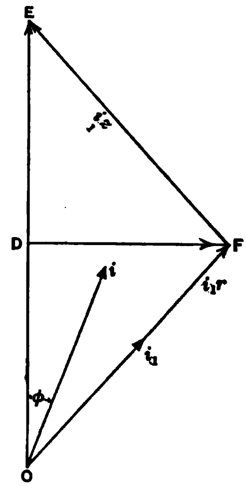

FIG. 280. Current and voltage relations with the connections according to Fig. 279.

OA and OC, are connected in series across the line, as the "running," or the main phase. The third winding, OB, is used for starting only with a resistance r and an impedance z (as nearly as possible pure inductance). After the motor has reached a considerable speed, the circuits of the starting device and of the phase OB are opened.

The voltages, when OB is open, are shown in Fig. 280: OE is the line voltage, Oi the current in the main phase AC, lagging behind OE because of the inductance of the winding. Voltages across r and z are represented by OF and FE respectively. The current i_1 through r and z is in phase with OF and lags considerably behind FE. The voltage across the starting phase is represented by the vector

DF, since this phase is connected between the middle point of *AC* and the junction of *r* and *z*. It will be seen from the sketch that the voltage *DF* may be made to lag considerably in phase behind *OE*, so as to satisfactorily imitate a two-phase combination. The diagram represents the conditions taking place when the auxiliary phase is open; as soon as a current begins to flow through *OB*, the phase relations become less favorable and the phase angle between *DF* and *OE* decreases. Still, by suitably selecting *r* and *z*, a torque can be produced sufficient for starting the motor.

350. Starting as Repulsion Motor.—There is a class of single-phase motors, Fig. 281, which possess quite a considerable starting torque; this is obtained, however, at the expense of a commutator and brushes. The particular motor, shown in the sketch, has a stationary field winding *FF*, connected to the line, and producing a pulsating field, as shown by the arrows. The armature *A* is similar to that of direct-current machines, and is provided with a commutator. The brushes *b b* are shifted against the direction of the field, and are short-circuited upon themselves, thus forming a closed armature circuit.

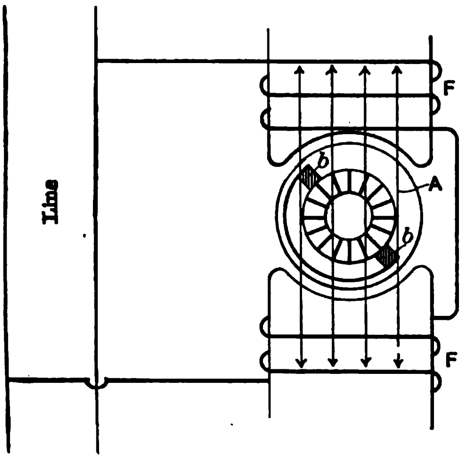

FIG. 281. Connections of a repulsion motor.

The pulsating field induces secondary currents in the armature, and the latter tends to move into such a position as to be subjected to minimum induction. This is impossible because the direction of the magnetic axis of the armature is determined by the position of the brushes; so the armature revolves continuously, trying to come into a stable position.

Such motors are called "repulsion" motors; they are seldom used at present on account of difficulties in commutation, and their so-called *series* characteristics. The speed of the motor greatly increases as the load decreases, the repulsion motor being in this respect similar to a direct-current series-wound motor (Fig. 215).

But there are good single-phase induction motors on the market, which *start as repulsion motors*. When a certain speed is reached, the commutator is automatically short-circuited, and the brushes are

removed from the commutator by a centrifugal device to avoid unnecessary friction. The objections against regular repulsion motors are not valid in this case, and the combination motors give good satisfaction, especially if starting does not have to be done too frequently.

351. EXPERIMENT 17-D. — Exercises in Starting Single-Phase Motors. — A regular single-phase induction motor with an auxiliary phase should be provided for this experiment. Connect up the motor as shown in Fig. 278, or according to the diagram supplied with the motor. Start the motor at no load, and determine the first current inrush, current taken by the running phase, current taken by the starting phase, and time which it takes for the motor to reach full speed. If any adjustment in the starting phase is possible, vary the conditions so as to obtain the best results, viz., minimum starting current, or minimum time necessary to reach full speed. If the motor can be started with a small load, put on a brake and determine maximum starting torque possible with various values of starting resistance in the auxiliary phase. Read line amperes, amperes in both phases, ohms starting resistance, and pounds torque.

If a regular single-phase motor is not available, use an ordinary three-phase induction motor, connected as per Fig. 279. The resistance r and the impedance z should at first be adjusted so as to get any starting torque whatever; then by varying their values the starting conditions should be improved, as far as possible. After this, either r or z should be kept constant, and curves taken showing the influence of the other factor. All currents, voltages and watts should be read, as far as possible, in the several branches of the circuit, so as to permit the construction of diagrams, like that shown in Fig. 280. Voltages and currents should also be read with the phase OB open, in order to see the influence of the current in this phase on the current and voltage relations in the circuit abc. If a starting torque can be obtained, the values of this torque should also be investigated.

Should the motor available for test be intended to be started as a repulsion motor, investigate the first current inrush, the power factor at start, time which it takes to reach the final speed, and maximum starting torque at which the motor can be started. If the brushes are adjustable, make a study of the influence of their position upon the starting characteristics of the motor.

Report the results of the tests, and construct vector diagrams showing current and voltage relations, such, for instance, as in Fig. 280. Plot curves giving starting amperes, torque, etc., as a function of the starting resistance or inductance, in case an auxiliary starting phase

was used. For the repulsion motor plot the same values to the position of the brushes as abscissæ.

352. EXPERIMENT 17-E. — Brake Test on a Single-Phase Induction Motor. — The purpose of this test and the curves to be taken are similar to those indicated in Experiment 17-B (§ 342). The wiring is much simpler, there being but one phase. Particular attention should be paid to an accurate determination of the pull-out torque; low overload capacity is one of the weakest points of the single-phase induction motor, so that the ratio of the pull-out torque to the full-load torque should be considered when judging the quality of the motor.

353. EXPERIMENT 17-F. — Performance of a Single-Phase Induction Motor from Losses. — The reasons for determining the performance of a single-phase motor from the losses, instead of by direct brake test, are the same as are given in § 343 for polyphase induction motors. The experiment is conducted in exactly the same way, as explained in § 345. The only difference in figuring out the results is in the expression for the secondary copper loss. It is shown in § 344 that per cent secondary copper loss in a polyphase induction motor is equal to per cent slip (the input into the secondary being equal to 100 per cent). In a single-phase motor, per cent secondary copper loss is *twice* as large as per cent slip. For instance, if the slip of the motor at a certain load is 4 per cent, the secondary copper loss amounts to 8 per cent; in other words, 8 per cent of the input into the secondary is converted into heat in the rotor windings. For a theoretical proof of this property of single-phase induction motors, see the references given in § 347.

NOTE. For some advanced and special tests on the induction motor see Chapter XXIX in Volume II.

CHAPTER XVIII.

ELECTRIC BATTERIES.

354. An electric battery is a device for generating electric current by means of chemical reactions. Or, in more scientific language, it is a device "for the conversion of the potential energy of chemical separation into the energy of an electric current" (Carhart).

A single cell of a battery consists of two electrodes of different substances immersed in a liquid (or a paste, as in dry cells). With proper materials an e.m.f. is produced between the electrodes, and if the circuit is closed, the cell becomes a source of power.

The production of current is accompanied by chemical reactions in the cell itself: The plates, or electrodes, and the solution (electrolyte) are gradually changed, and finally become *neutral* with respect to each other; here the reaction stops, and the cell is said to be completely discharged or exhausted.

Some kinds of cells require renewing of the plates and of the solution in order to be able again to generate current. Others need only recharging by an electric current sent through the battery in the opposite direction; this current reduces the elements of the cell to their original state. Cells of the first type are called *primary cells;* those of the second type, *secondary or storage cells.* The reason for these names is that in the first type of cells electric current is obtained directly from the chemicals constituting the cell; whereas a storage cell merely returns the electric power previously put into it.

Primary batteries are used only where comparatively small amounts of energy are required and the service is intermittent: For instance, in bell and telephone work; in telegraph, signal and alarm service; for igniting gas engines, etc. Storage batteries are used somewhat for the same class of work, but their principal field of application is in light and power stations, in electric railway substations, etc., where it is of advantage to store large amounts of electrical energy during periods of small demand for use during periods of large demand. Moreover, a storage battery is an excellent reserve in case of an accident to the generating machinery.

PRIMARY CELLS.

355. The following types of primary cells are in most common use in this country:

(1) Gravity cell;
(2) Leclanché cell;
(3) Edison cell;
(4) Dry cells.

The general features of these cells are described below; instructions for installing the cells and detailed recipes of chemicals usually accompany "wet" cells.

356. Gravity Cell. — The positive electrode is of zinc, and is placed in the top of the cell. The negative electrode is of copper, and is placed on the bottom of the jar. The copper electrode is surrounded with crystals of copper sulphate ($CuSO_4$), known commercially as blue vitriol or bluestone; the jar is filled with water. A little sulphuric acid, or better, a weak solution of zinc sulphate ($ZnSO_4$), is added on top of the water.

During the action of the cell, zinc (Zn) replaces copper (Cu) in copper sulphate; zinc sulphate is formed in the upper part of the jar. Metallic zinc gradually disappears, and metallic copper is deposited on the copper electrode.

The name "gravity cell" is due to the fact that copper sulphate solution is kept below zinc sulphate without mixing with it, merely because of the difference in the specific gravities of the two solutions. The separating "blue line" must be kept about midway between the electrodes.

357. Leclanché Cell. — The positive electrode is again of zinc, the negative consists of carbon surrounded with peroxide of manganese (MnO_2). A solution of sal ammoniac (NH_4Cl) is used as electrolyte. When the circuit is closed, zinc (Zn) displaces ammonium (NH_4) in the solution, forming zinc chloride ($ZnCl$). The ammonium breaks up into ammonia gas (NH_3), which either unites with water or escapes, and free hydrogen (H), which is liberated at the surface of the carbon.

Without peroxide of manganese, this hydrogen would soon completely "polarize" the battery: Bubbles of hydrogen surrounding the carbon would form a layer of considerable electrical resistance and of an appreciable counter-e.m.f. In the presence of peroxide of manganese, which is rich in oxygen, hydrogen unites with the oxygen and forms water. For this reason, manganese peroxide is called a "depolarizer."

This depolarizer, being solid, does not act promptly enough, so that the cell requires periods of rest between periods of action. Therefore,

the Leclanché cell is suitable for open-circuit work only, such as bell or telephone service, where the circuit is closed for short intervals, and sufficient time of rest is afforded for the depolarizer to oxidize the hydrogen.

358. Edison Primary Cell. — The elements employed in this cell are: zinc (Zn) and black oxide of copper (CuO) in a solution of caustic soda ($NaOH$). A layer of heavy mineral oil is poured on top of the solution, to prevent it from creeping up the zinc plates.

When the circuit is closed, the water of the solution is decomposed into nascent oxygen and hydrogen. The oxygen goes to the zinc plate and unites with it, forming oxide of zinc. This, in its turn, is dissolved by the caustic soda solution, forming zincate of soda (Na_2ZnO_2). The hydrogen unites with the oxygen contained in the oxide of copper plate, forming water and leaving behind metallic copper. As the oxide plate is porous, this action goes on, when the cell is in service, until the oxide plate is reduced throughout its entire mass to metallic copper in a finely divided state.

Thus, in this cell, copper oxide acts as the negative plate, and at the same time as a very effective depolarizer for hydrogen. Therefore the Edison cell is very well adapted for closed-circuit work. In fact, it has a greater capacity for work per unit weight than any other cell on the market, either primary or secondary.

359. Dry Cells. — The solutions present in the above-described types of "wet" cells are objectionable in some cases, making the cells rather difficult to handle; moreover, renewals require some skill and experience. This circumstance led to the introduction of so-called *dry cells*, which in many instances have replaced wet cells, and are constantly increasing in public favor.

A dry cell is set up in the factory and sealed; when it is exhausted in use, it is simply replaced by a new cell, no renewals being attempted. Strictly speaking, these cells are not dry, but the active solution is held absorbed by some porous substance, in the form of a paste. Being sealed, the cell is as convenient for handling as if it were actually dry.

In their chemical action the dry cells are similar to the Leclanché cell described above. The containing cup is made of zinc, and serves as the positive electrode. The negative electrode is a vertical carbon rod in the center of the cell. The intervening space is filled with a mixture of peroxide of manganese, powdered carbon and some moisture-retaining material, such as sawdust. The whole is saturated with a solution of sal ammoniac and the cell is sealed. The principal reaction, as in the Leclanché cell, consists in the formation of zinc chloride and in depolarization of hydrogen by the peroxide of manganese. Various

binding and other substances are usually added to the paste by different manufacturers, and the actual reactions are more complicated than the one described above.

360. Testing Primary Cells. — The most important operating characteristics for which primary cells are usually tested are:

(1) Internal e.m.f. and terminal voltage.
(2) Internal resistance.
(3) Amount of polarization and promptness of recovery.
(4) Useful life under given conditions of service.

These tests are described below in detail.

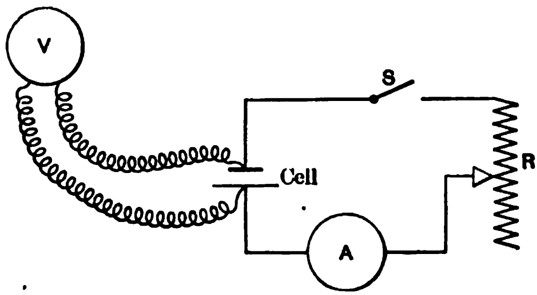

FIG. 282. Electrical connections for testing a cell.

361. Measurement of Electromotive Force.—The electromotive force on open circuit and the terminal voltage on closed circuit are measured with any ordinary voltmeter (Fig. 282), unless even a small voltmeter current appreciably alters the condition of the cell. Good modern voltmeters take but 0.01 ampere with full-scale deflection, so

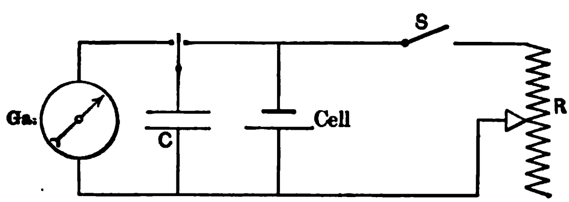

FIG. 283. Measuring the voltage of a cell by means of a condenser and a ballistic galvanometer.

that this current may be considered negligible under ordinary circumstances (except in standard cells; see § 62).

If such is not the case, the voltage may be measured as is shown in Fig. 283: A condenser C is connected across the terminals of the cell under test, and is charged at the voltage of the cell, by pressing to the right the two-way key shown above the condenser. Then the condenser is discharged through the ballistic galvanometer Ga (§ 119)

by pressing the key to the left; the deflection is noted. Then the same condenser is charged by a standard cell and again discharged through the galvanometer. The ratio of the deflections gives the ratio of the voltages compared. As the voltage of the standard cell is known, the voltage of the cell under test may be calculated.

If very accurate results are required, the voltage of the cell under test is compared to that of the standard cell by means of a potentiometer (see § 63).

362. Measuring Internal Resistance. — Suppose the e.m.f. of a cell on open circuit to be E; let the terminal voltage be e when the cell is closed on an external resistance R (Fig. 283). Then the unknown internal resistance x of the cell may be determined from the conditions that the current

$$i = \frac{e}{R} \text{ and also } i = \frac{E - e}{x},$$

or

$$\frac{e}{R} = \frac{E - e}{x},$$

whence

$$x = R\frac{E - e}{e}.$$

In reality, the drop $(E - e)$ is due not only to the internal resistance but also to the counter-e.m.f. of polarization, which increases with time (Fig. 284). Therefore, in performing the above test, it is essential *to measure the voltage e immediately upon closing the circuit,* before any polarization has set in. Besides this, the cell should have had a sufficient period of rest, in order that all previous polarization may have been removed. The measurements may be conveniently performed with the connections shown in Fig. 283. The voltage at no load is read by charging and discharging the condenser with the two-way key, having the switch S open. Then the two-way key is pressed to the right, the switch S is closed, and immediately afterward the key is again pressed to the left. The galvanometer deflection gives the terminal voltage e. The galvanometer is supposed to be calibrated, as before, with a standard cell.

The resistance of a cell cannot be measured with an ordinary Wheatstone bridge, because the e.m.f. of the cell would entirely vitiate the result. One way out of this difficulty is to measure the resistance of two identical cells connected in opposition, so that their e.m.f.'s destroy each other. Another method is to use a Wheatstone bridge with alternating currents (see § 21).

363. Polarization and Recovery Tests. — The connections are made as in Fig. 282, or as in Fig. 283, according to whether or not it is permissible to use a voltmeter (see § 361). The cell is closed on a certain resistance R, and terminal voltages are measured at stated intervals, with the switch S closed and open. The results are plotted as in Fig. 284.

The curve marked "Terminal Volts" refers to the readings with the circuit closed; the curve marked "Internal e.m.f. on Closed Circuit" gives voltmeter readings immediately after the switch S has been opened. The current is read directly on an ammeter; the internal

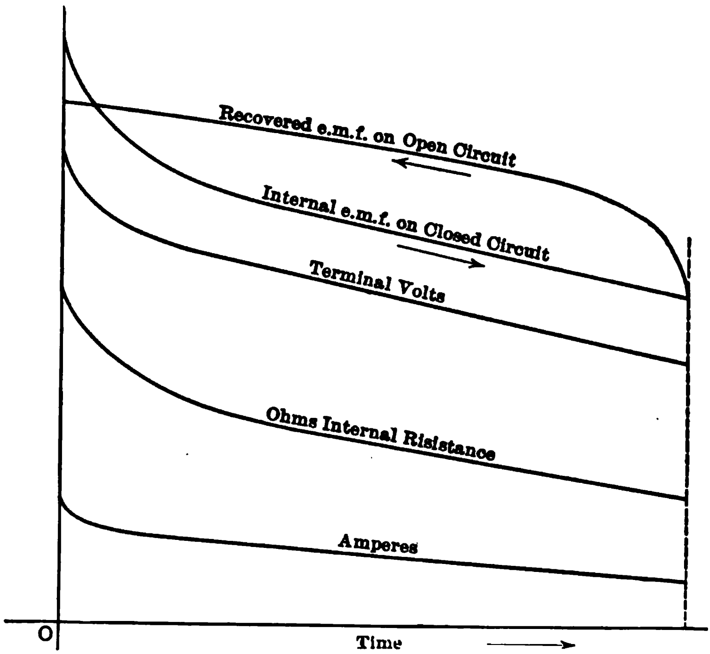

FIG. 284. Performance curves of a primary cell.

resistance of the battery (§ 362) is calculated by dividing the differences of the ordinates of the two voltage curves by the corresponding currents. The circuit must be open just long enough to read the voltmeter, and then closed again.

At the end of a certain period of time, say one or two hours, the circuit is permanently opened, and the cell is allowed to recover from polarization. The voltage gradually rises as shown by the upper curve.

The test, in order to be conclusive, must be repeated on several cells of the same type, and with various rates of current; also with cells closed for different lengths of time.

364. Useful Life of Primary Cells. — The useful life of a cell depends essentially upon the character of service for which it is used; therefore the test for life must approximate, as far as possible, the actual conditions of service. If the cell is intended for closed-circuit work, it is closed during the test on a resistance equal to that of the apparatus which it is intended to supply, and is kept in the circuit until the current falls below that sufficient for the purpose.

In testing open-circuit cells, the circuit must be periodically closed and opened, in order to give the cell some time to recover from polarization. It is convenient to have, for such a test, a clock provided with contacts on its face: the minute hand carries a wiping contact which closes the circuit for a few minutes at desired intervals of time. If several cells are tested simultaneously, the circuit of each cell is closed by a separate relay. All the relays are connected in series and are operated from an auxiliary battery: the clock merely closes the circuit of this battery.

Terminal volts are plotted to days of service as abscissæ, until the end of the useful life of the cell. Such curves, plotted for different cells, permit to select the kind most suitable for the service.

Some prefer to keep the current constant during the life test, instead of keeping constant resistance. An advantage of this method is that the test is shorter; at the same time it is fair, because all the competitive cells are tested under identical conditions.

365. EXPERIMENT 18-A.—Testing Primary Cells.—The tests are described in §§ 360 to 364. The characteristics of the principal types of primary cells will be found in §§ 355 to 359. (*a*) Measure the internal resistance of the cell by the three methods described in § 362. (*b*) Perform a short polarization and recovery test, described in § 363 and represented by the curves in Fig. 284. The life test could not be performed during a laboratory period; but it is advisable to keep in the laboratory a few cells on life test, as described in § 364, and let each student enter his readings on the permanent log.

Report. Give the internal resistance of the cells tested; plot performance curves, similar to those in Fig. 284. Make rough sketches of the cells experimented with and mark the substances used in them; also give the principal chemical reactions in the form of equations.

CHARACTERISTICS OF STORAGE CELLS.

366. Storage cells (also called electric accumulators) are devices used for storing electrical energy (in chemical form), which may be

delivered at a later time. The part which storage batteries play in the distribution of electrical energy is much the same as that of a water storage tank in a water supply system (Figs. 285 and 286). Without the tank the pumps have to supply a variable demand; their capacity must, therefore, be sufficient for the *maximum* demand. Moreover they must be operated 24 hours a day, the power consumption is much increased and the efficiency consequently reduced, to say nothing of the excessive mechanical strains imposed by sudden variations of the load. A water tank of sufficient capacity remedies all this; the capacity of the pumps needs to be sufficient for the *average* demand only, and they may be operated at practically full load. When the demand is below the

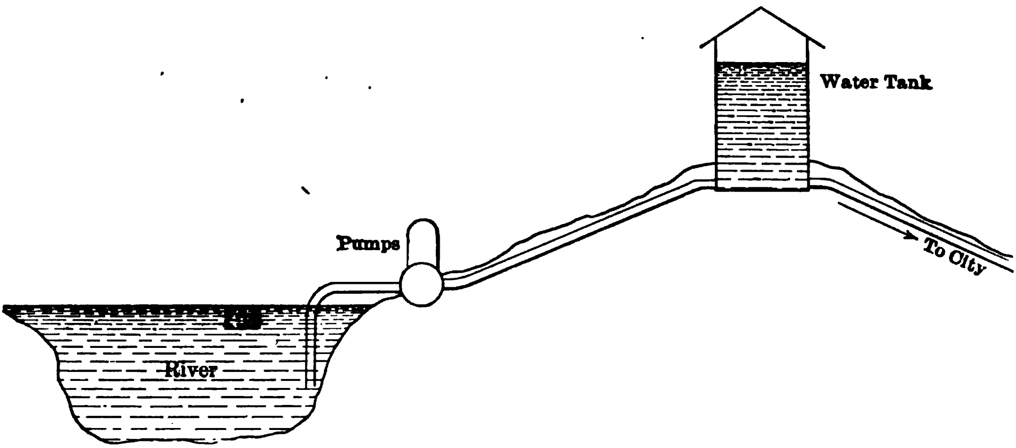

FIG. 285. A water-supply plant, analogous to an electric plant with a storage battery.

average, the excess of water pumped simply raises the level in the tank. When the demand is above the average, the tank supplies the necessary excess of water into the city mains. In addition to this, the tank allows a more constant pressure to be maintained in the mains, with variable load. Similarly, in an electric power house without storage batteries, the generators have to supply the variable demand and are subjected to all the disadvantages resulting therefrom, viz., their capacity must be sufficient for the heaviest overloads which may occur, the machines must be operated 24 hours a day or at least as long as there is even the smallest demand for light and power; the engines are subjected to severe mechanical strains and are working under the most unfavorable conditions, as far as efficiency is concerned — namely, at variable load.

When a storage battery is connected in parallel with the **generators** (Fig. 286) the latter need have a capacity sufficient only for the *average* daily load, and may be worked practically all the time at this load. When the load is below normal, the excess energy is sent into the batteries, charging them. At the hours of maximum demand (peaks of the load), the battery discharges into the line in parallel with the

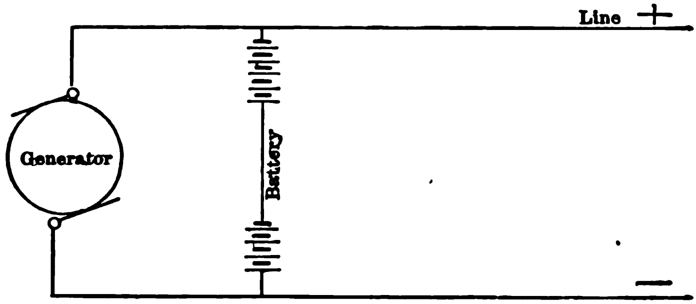

Fig. 286. A generator and a storage battery supplying a line in parallel.

generators. During the hours of very small demand the engines may even be shut down, the battery alone supplying the current. The efficiency of the plant is thus increased, and a steadier pressure maintained with fluctuating loads.

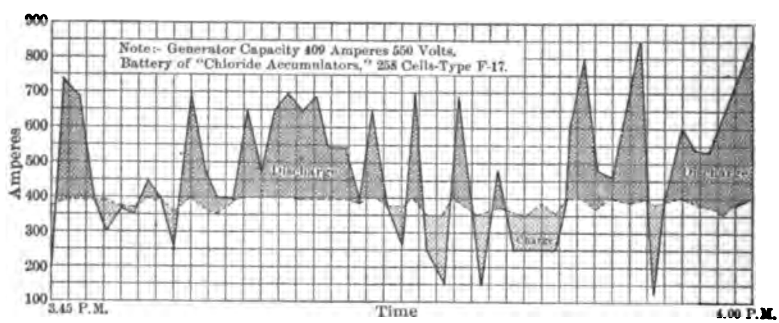

Fig. 287. Effect of a battery in steadying generator load.

Fig. 287 shows the effect of a storage battery in steadying the generator load; while the total load varies between 150 and 850 amperes, the generator load is kept at an average of between 350 and 400 amperes. Fig. 288 illustrates the influence of a storage battery, in maintaining a constant voltage. Without the battery, the voltage fluctuates between 108 and 122 volts; the battery limits the fluctuations between 113 and

118 volts. Both diagrams represent actual curves, observed experimentally in certain power houses.

The limitations which at present prevent the universal use of storage batteries are: (1) their comparatively high first cost and depreciation; (2) additional complications resulting from extra apparatus needed for controlling and charging the batteries, and (3) the amount of care required in their maintenance. There are many cases, however, especially in city electric-railway work, where the advantages gained by the use of batteries by far outweigh the disadvantages; in such cases storage batteries are extensively used.

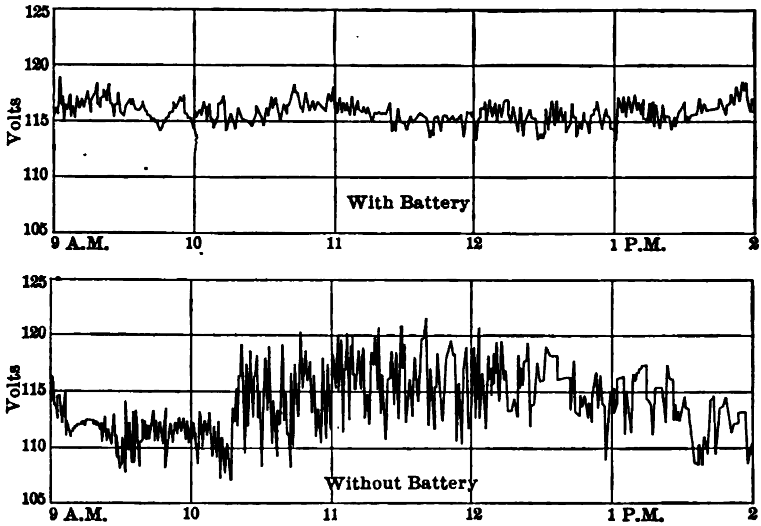

FIG. 288. Effect of a battery in steadying the line voltage.

367. Construction and Chemical Action of Storage Cells.—An electric storage cell is a voltaic couple, in which plates of spongy lead (Pb) and peroxide of lead (PbO_2) are used as active materials (Fig. 289). These plates are immersed in dilute sulphuric acid (H_2SO_4) which acts as an electrolyte. When the cell discharges, both active materials are partially converted into lead sulphate ($PbSO_4$), and the acid thus becomes more dilute. On charging, a reverse action takes place, the plates being again reduced to lead peroxide (positive plate) and spongy lead (negative plate). The specific gravity of the electrolyte increases to its normal value, and the cell is again ready for discharge.

These chemical changes may be represented by a formula, thus:

$$PbO_2 + Pb + 2H_2SO_4 \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} 2PbSO_4 + 2H_2O.$$

In reality the chemical reactions are much more complicated and are hardly known at present in all details. The above fundamental equation is however, sufficient for a general understanding of the operation of storage batteries.

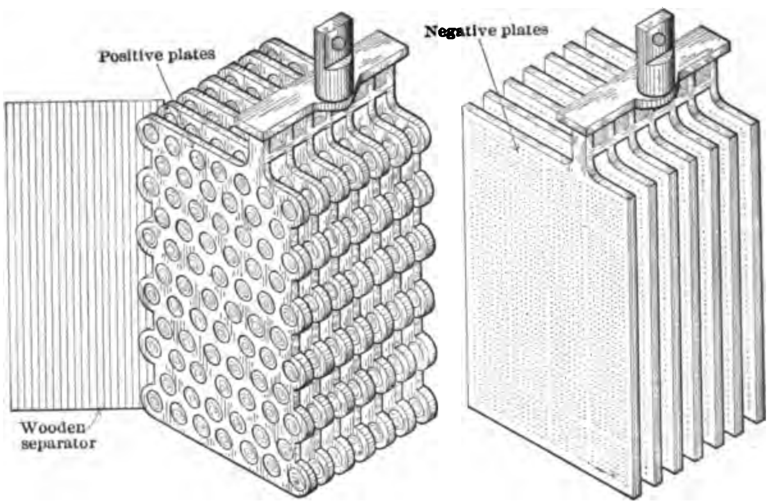

FIG. 289. "Chloride" positive and negative plates, and a separator.

The plates shown in Fig. 289 represent one of the types used by the Electric Storage Battery Co. The negative plate to the right consists of a flat chamber made of two thin perforated lead sheets, filled with active material. The positive plate to the left consists of a supporting grid with buttons rolled from lead ribbon inserted in it. A wooden separator is shown to the left.

Impurities in lead and in the electrolyte produce local chemical action which may ruin the plates. It is important, therefore, to use pure materials. The manufacturers insist in particular that chemically pure sulphuric acid and distilled water be used.

There are two types of battery plates, called Planté type and Faure type, after their respective inventors. In Planté plates the active materials, spongy lead and lead peroxide, are "formed" on the plates themselves, by successive charge and discharges, or by chemical action.

In the Faure or "pasted" plates the active materials are applied mechanically to a supporting grid; this grid is of lead; it supports the active materials and conducts the current to the terminals. The pasted materials usually require some formation by electrical or chemical processes before they are brought to their final form.

For details of construction of various types of plates and of the manufacturing processes the reader is referred to Lamar Lyndon's *Storage Battery Engineering*.

368. Voltages during Charge and Discharge. — A fully charged storage cell has an e.m.f. of a little over 2 volts on open circuit. If allowed to be discharged indefinitely the voltage will at first remain

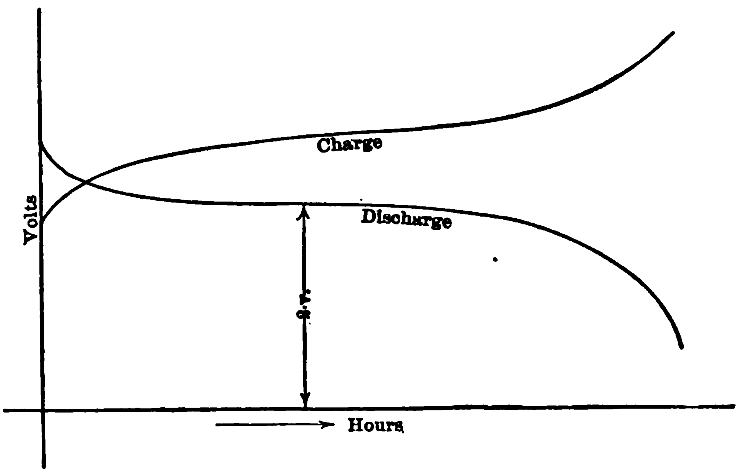

FIG. 290. Curves of charge and discharge of a storage cell.

practically constant at about 2 volts, then will gradually fall off, at first slowly, then more and more rapidly, down to zero (Fig. 290).

The voltages given in the curve are supposed to be measured while a normal discharge current is flowing through the cell. The voltage drop in the cell is due to the internal resistance of the cell and to some polarization on the surface of the plates.

A complete discharge down to zero voltage would be impracticable, because for all ordinary purposes the terminal voltage of the battery must be constant within rather narrow limits. Moreover, such a complete discharge would ruin the battery. The reason for this is that lead sulphate ($PbSO_4$) which is formed during discharge is practically an insulator, and if too much of it is allowed to be formed on the plates, the reduction back to Pb or PbO_2 is very difficult, if not impossible. Enough lead or lead peroxide must remain on the plates to keep down

their resistance. Otherwise, charging current cannot flow through the active material and effect a regeneration of the battery.

In practice, it is considered that a cell requires a new charge when the voltage has dropped to 1.75 volts (or, better, 1.8 volts). This voltage is measured with the battery supplying a current which corresponds to the eight-hour rate of discharge (see § 371).

When the cell is being charged, the external voltage applied at its terminals must be high enough to overcome the counter-e.m.f. of the cell and to force the charging current through its ohmic resistance. At the beginning of a charge the charging voltage is a little above 2 volts per cell. As the battery becomes recuperated, this voltage must be gradually increased; until at the end of the charge it is necessary to apply about 2.6 volts in order to get full charging current through the cell. The end of the charge is also recognized by an excessive liberation of gases (boiling) due to a decomposition of water in the solution.

The best indication, however, of a complete charge is that the specific gravity of the acid has reached its maximum and remains constant. Referring to the fundamental chemical reaction, given in § 367, this means that all sulphate is liberated and the plates consist of pure lead and lead peroxide..

369. Capacity of Storage Batteries. — The *capacity* of a cell, or the amount of electricity that it can give on discharge, is measured in *ampere-hours;* a cell which can supply 25 amperes for 8 hours, before the lower limit of the e.m.f. — 1.8 volts (or 1.75 volts for some makes) — is reached, is said to have a capacity of $25 \times 8 = 200$ ampere-hours. Experience shows that the capacity of a cell depends essentially on the rate of discharge. The more rapid the discharge the less is the capacity; thus the above cell, if discharged at a rate of 100 amperes, would be completely discharged in one hour instead of two hours. Therefore, *in speaking of the capacity of storage batteries it is always necessary to mention the number of hours in which the battery is supposed to be discharged.* It is customary to rate stationary batteries on the basis of an eight-hour discharge, and batteries used on electric automobiles on the basis of a four-hour discharge. Storage batteries used in electric railway substations, for taking up fluctuations of the load, are usually rated on the arbitrary basis of one-hour discharge.

If a battery is intended to be discharged within a shorter period of time than the normal, its rated capacity must be reduced in a ratio usually given by the manufacturer. Roughly speaking, if the capacity is 100 per cent at an 8-hour rate, it is about 93 per cent at a 6-hour rate, 75 per cent at a 3-hour rate, and only 50 per cent at a 1-hour rate (see table in § 371).

One of the reasons for a decrease in capacity at higher rates of discharge is that the electrolyte cannot circulate as rapidly as required, thus diluting the acid in the pores of the plates before fresh acid can take its place. Another reason is, that a layer of lead sulphate is formed on the surface of the plates, preventing further action.

370. Testing Storage Cells. — The principal points to be investigated in the performance of a storage cell are:

(1) *Behavior at discharge.*
  (a) Variations of terminal voltage.
  (b) Variations of density of the electrolyte.
  (c) Influence of the rate of discharge on capacity.

(2) *Behavior at charge.*
  (a) Variations of terminal voltage.
  (b) Variations of density of the electrolyte.

(3) *Electrical efficiency.*

(4) *Internal resistance.*

(5) *Weights and dimensions per ampere-hour output.*

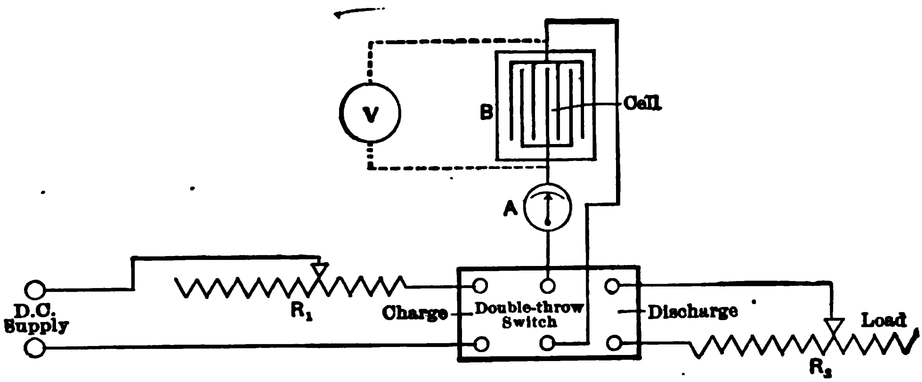

FIG. 291. Connections for testing a storage cell.

There are a few more practical tests, such as influence of temperature, loss of charge by local chemical action, durability in service, etc., which in spite of their importance cannot usually be performed in the short time allotted to students in the laboratory.

Connections convenient for the test of a storage cell are shown in Fig. 291. By means of a double-pole double-throw switch the cell *B* can be connected either to the source of power (for charge) or to a resistance (for discharge). *A* is a two-way reading ammeter, *V* is a voltmeter connected across the terminals of the cell.

The tests above enumerated are described below more in detail.

371. Charge and Discharge Characteristics.—The cell under test must be fully charged before beginning the experiment on discharge characteristics. The end of the charge is best recognized by the density of the acid, which reaches its maximum and remains constant. The voltage also reaches its maximum and remains constant. The absolute values of density and voltage are usually given by the manufacturer of the cell, and may vary within certain limits.

The time of charging should not be less than three hours if the cell has been completely discharged. At a higher rate of charging, the electrolyte heats up and the liberated gases cause it to boil; with the result that active material is washed out of the plates, and the useful life of the cell is thereby reduced. Below this extreme, the amount of electrical energy necessary for charging is essentially independent of the charging rate.

It should be well noted that the acid ought to have the prescribed density when the cell is fully charged. The density may be corrected by the addition of distilled water or of acid, as the case may require: this should be done only when the cell is fully charged, *and under no other circumstances.*

After the cell has been fully charged, the switch (Fig. 291) is thrown over to the discharge side. The current is adjusted to the desired value and maintained at this value until the end of the discharge. The curve of voltage on discharge has the general aspect as shown in Fig. 290: it drops rapidly at the beginning and at the end of the discharge, and remains practically constant during the interval between. Therefore, readings must be taken every few minutes at the beginning and at the end of the run; a few check readings are sufficient for the rest of the time. Read volts, density of acid (on a hydrometer) and its temperature; stir the liquid before reading the hydrometer, so as to measure the true average density.

The constant current of discharge, multiplied by the number of hours of the test to the time when the cell is considered discharged, gives the ampere-hour capacity of the cell. This capacity, multiplied by

Hours Discharge.	Final Voltage.	Relative Value of Current.	Relative Capacity in Amp. Hours.
8	1.75	1	8 (100%)
3	1.70	2	6 (75%)
1	1.60	4	4 (50%)
$\frac{1}{3}$	1.40	8	$2\frac{2}{3}$ ($33\frac{1}{3}$%)

the *average* voltage during discharge, gives the watt-hour capacity. The test may be repeated with various rates of discharge, and the influence determined, which the time of discharge has on the capacity of the cell.

The table on the preceding page gives the voltages at which the discharge should be stopped (for "Chloride" batteries). In every case the voltage is to be measured with a discharge current, flowing at the corresponding rate.

372. Cadmium Tester. — In order to ascertain the state of charge on both plates, a cadmium tester is sometimes used. It consists of a stick of pure cadmium placed in the acid of the cell under test. It is well to have the cadmium protected by a hard rubber tube with perforations for the circulation of the acid.

At the end of the charge the voltmeter must show about 2.45 volts between lead peroxide and cadmium, and about 0.10 volt between the lead plate and cadmium. This is a more or less positive indication of the end of the charge. The voltage between the two plates is equal to the sum of the two readings:

$$2.45 + 0.10 = 2.55 \text{ volts.}$$

The same tester can be used to ascertain the end of discharge. In this case the voltages are + 1.95 and − 0.20 volts respectively; the battery voltage is

$$1.95 - 0.20 = 1.75 \text{ volts.}$$

In case it is found that one of the plates is not fully charged, the charge must be continued until the cadmium tester shows the required voltage. Or, if it is feared that an excessive charge may damage the other plate, the plate which requires additional charging may be charged in a separate cell.

A cadmium tester gives reliable indications in the hands of an experienced observer, especially when many tests are made on batteries of the same type. Otherwise, it is safer to judge of the state of the charge from the acid density and the voltage.

373. Internal Resistance. — The determination of the *true* ohmic resistance of storage batteries is rather difficult because this resistance is very small, is variable, and is to some extent masked by the effect of polarization. Moreover, it is not the true resistance, but rather the *virtual* resistance of the cell that is interesting to the user, this virtual or equivalent resistance representing the total drop of voltage in the battery, due to whatever causes. The simplest method to determine the resistance R of a cell would be to observe the voltage E_0 of the

battery on open circuit, and then immediately note the voltage E with a certain charging current I flowing through the battery. Then, evidently,

$$R = \frac{E - E_0}{I}.$$

A better method is to measure two terminal voltages E_1 and E_2, corresponding to two different values I_1 and I_2 of charging current. We then have

$$\begin{cases} E_1 - p - E_0 = RI_1; \\ E_2 - p - E_0 = RI_2; \end{cases}$$

where p is the counter-e.m.f. of polarization. Eliminating p and solving for R, we obtain

$$R = \frac{E_1 - E_2}{I_1 - I_2}.$$

An objection to this method is that the e.m.f. p of polarization is not quite constant with various rates of charge. Another objection is that the difference $E_1 - E_2$ is rather small; naturally, this impairs the accuracy of the result. It is advisable to perform a large number of tests with various values of I_1 and I_2 and to take an average of the calculated values of R. Experience shows that more consistent results are obtained on discharge than on charge; the same formula is used, as that given above.

Another way of measuring the resistance of a cell is the so-called "break" method which is considered by some to be more reliable. A certain value of discharge current is adjusted through the cell, and when the conditions become steady, the circuit is suddenly opened. The pressure, as shown on the voltmeter, rises instantly by a certain amount and then continues to rise *gradually* as the polarizing bubbles of gas disappear. It may be assumed with a considerable degree of accuracy that the first (instantaneous) rise in voltage corresponds entirely to the ohmic drop, since the bubbles of gas are evidently the same as a moment before when the circuit was closed. From this rise in voltage and the current formerly flowing through the battery, the internal resistance can be calculated. Suppose, for example, that the voltage rises from 1.8 volts to 1.9 volts when the switch is opened, with 100 amperes flowing through the battery. The resistance of the cell is $0.1 \div 100 = 0.001$ ohm.

374. EXPERIMENT 18-B. — Testing Storage Cells. — The experiment is performed as described in §§ 370 to 373. The readings during charge and discharge are taken at comparatively infrequent intervals; it is possible, therefore, to test simultaneously more than one

cell. One voltmeter, and one milli-voltmeter with several ammeter shunts, are sufficient for all the cells. Some of the cells may be charging while others are discharging. Tests at low rates may be continued throughout several consecutive days by different observers, who may work out the results together.

At the end of the experiment, measure all the dimensions of the cell and of its elements, so as to be able to make a drawing to scale. Determine the weight of the plates, of the electrolyte and of the complete cell. Do not keep the negative plates out of the liquid longer than necessary; they may be damaged by the action of the atmosphere.

Report.

(*a*) Capacity of the cell tested, in ampere-hours and in watt-hours at various rates of discharge.

(*b*) Corresponding efficiencies, both for ampere-hours and for watt-hours; which latter is always lower than the former, because the average voltage is lower at discharge than at charge.

(*c*) Curves of variation of voltage and of acid density at charge and at discharge.

(*d*) Virtual and true resistances of the cell.

(*e*) Capacity in ampere-hours per pound of complete cell; also per pound of plates.

(*f*) Charge and discharge rates in amperes per square foot of plate surface.

(*g*) A complete drawing of the cell.

OPERATION AND CONTROL OF STORAGE BATTERIES.

375. Storage batteries are usually connected in parallel with generators, as shown in Fig. 286. Auxiliary apparatus necessary for the operation of batteries comprises:

(*a*) Switches, circuit-breakers, measuring instruments, etc.

(*b*) Means for charging the battery, and for regulating its current and voltage on charge and discharge.

The devices mentioned under (*a*) are similar to those used with direct-current generators and motors; those under (*b*) are peculiar to storage batteries. Various methods are used for charging and controlling the output of batteries, the determining factors in the selection of the system of control being:

(*a*) Purpose of the battery;

(*b*) Its size;

(*c*) Permissible limits of current and voltage fluctuations;

(*d*) Cost of the system;

(*e*) Whether hand or automatic control is desired.

The most important systems of control in practical use are described in the following articles, beginning with the simplest system and including the most perfect automatic equipments.

376. Charging Two or Three Parts of a Battery in Parallel. — The simplest method for charging and regulating storage batteries is shown in Fig. 292. The battery is divided into two halves which are connected in series for discharging, and in parallel for charging. This is done in order to secure a sufficient voltage for charging, without affecting the line voltage, maintained by the generator. An example will make this clearer. Consider a battery intended for an ordinary 110-volt lighting circuit: The voltage of each cell at the end of discharge is about 1.8 volts; therefore the number of cells required is $110 \div 1.8 = 62$. But the voltage necessary with this number of cells at the end of a charge is $= 2.6 \times 62 = 161$ volts, which is far above the line voltage.

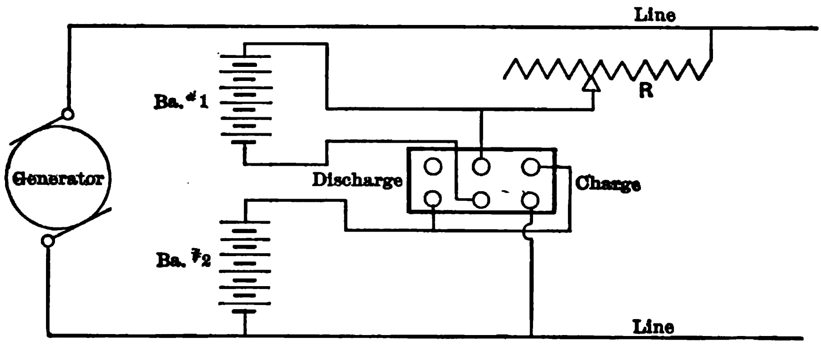

FIG. 292. Charging two halves of a storage battery in parallel.

With the battery divided into two halves in parallel, only 80.5 volts are required for charge; the excess voltage of the line is taken up by the rheostat *R*. Battery output on discharge is also regulated by this rheostat. This method, although very simple, is seldom used except in small installations, where the loss of power in the rheostat is not objectionable.

A more economical method is to divide the battery into three equal parts; let them be denoted *A*, *B* and *C*. The parts *A* and *B* are first charged in series for one-half of the time necessary for full charge; then *B* and *C* are charged in series for one-half of the time, and finally *C* and *A* for one-half of the time. Less energy is wasted in the resistances with this arrangement, although it takes longer to charge the battery. The voltage at the end of the charge is $\frac{2}{3} \times 161 = 107$ volts.

Other combinations are also possible; for instance, *A* and *B* may be connected in parallel with each other and in series with *C*. The set

is charged at the full rate until C is completely charged. Then C is disconnected, A and B are connected in series, and the charge is completed.

377. EXPERIMENT 18-C. — Charging Batteries in Sections. — Wire up the two halves of a battery, as in Fig. 292, and make connections to a suitable generator. Provide a load in the form of adjustable resistances, and operate the installation under the following conditions, viz.:

(*a*) Both the battery and the generator supplying power to the line.

(*b*) The battery being charged, the generator at the same time supplying power to the line.

(*c*) The battery alone supplying power, the generator shut down.

(*d*) The generator working alone, the battery being disconnected for inspection and repairs.

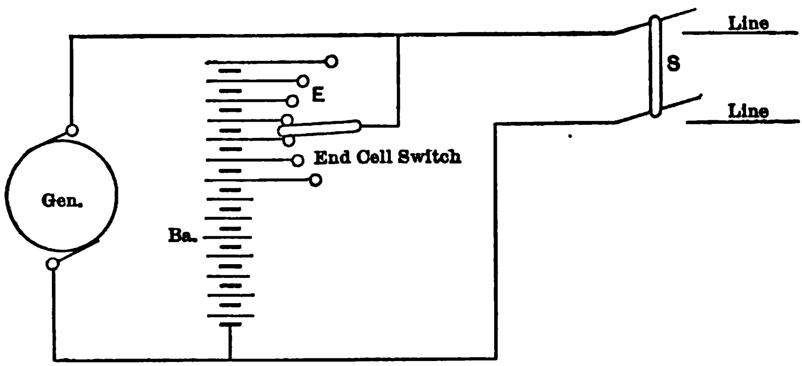

FIG. 293. Use of a single end-cell switch.

For each of these conditions select a few characteristic loads (light load, medium load, full load and overload) and take all the necessary ammeter and voltmeter readings, so as to have a complete record of the electrical relations in the circuit, with special reference to the performance of the battery. Observe voltage and current fluctuations, when the load is varied, first gradually and then suddenly.

Devise a convenient arrangement of switches for charging the battery in three parts, as explained in the preceding article. Connect the battery accordingly and observe the process of charging.

378. End-Cell Switches. — In many small installations there is no demand for current during the day. In such cases battery connections shown in Fig. 293 are used. The battery is charged during

the day, when the main switch S is open; the voltage on the generator being raised to the required voltage (say 161 volts), for charging the battery. During discharge the battery voltage and output are regulated by the so-called *end-cell switch* E, by means of which more cells may be connected into the circuit, in proportion as the voltage of each cell drops during the discharge.

End-cell switches are sometimes used also in installations where charging is done by means of special machines, so-called "boosters" (Fig. 296). Storage batteries in stations and substations of electric lighting companies in most large cities are regulated by end-cell switches and charged by boosters. Large end-cell switches are sometimes

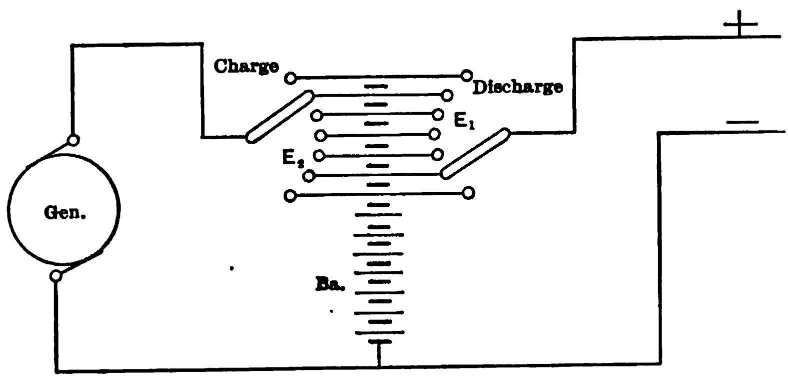

FIG. 294. Use of a double end-cell switch.

operated by auxiliary electric motors, which are started or stopped either by the switchboard attendant, or automatically by a contact voltmeter.

The contact on the arm of an end-cell switch must be wide enough, so as not to open the battery circuit while the arm is moved from one segment of the switch to the next. On the other hand, when the arm bridges two adjacent segments, it apparently short circuits the cell connected to these two segments, which is not permissible. Therefore, the arm contact is made in two parts, with a *protective* resistance between, this resistance limiting the current in the short-circuited cell during the instant when the arm is moved from one contact to the next.

In some cases it is not practicable to have the main switch opened, while the generator voltage is being raised for the charge; at the same time the size of the installation may not warrant the complication of a booster set. Two end-cell switches are used in such cases, as shown in Fig. 294. By means of the end-cell switch E_1 the required voltage is

maintained on the line, while the charge is regulated by the generator field rheostat and the end-cell switch E_2. With this scheme, the end cells are carrying the sum of the charging current and the line current, and are therefore charged faster than the rest of the battery. Actual practice does not show, however, any disadvantage of such an arrangement, provided the charging is done during the hours of small demand.

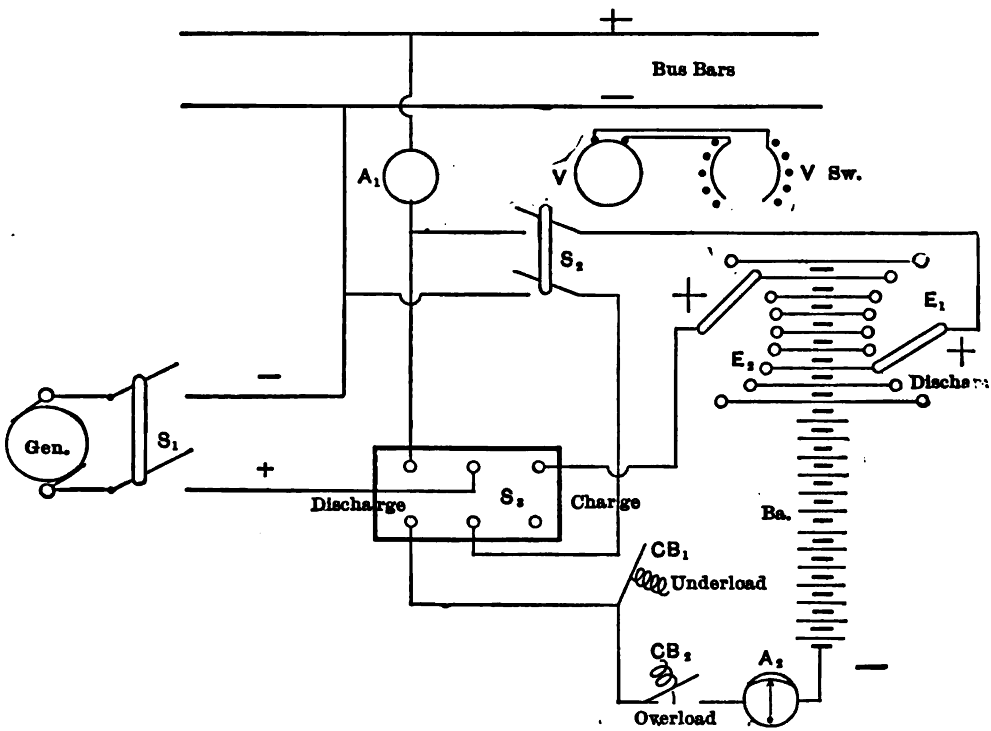

FIG. 295. Details of connections of a battery controlled by a double end-cell switch, as in Fig. 294.

It will be easily seen that more contact points are necessary with a double end-cell switch than with a single end-cell switch.

Fig. 295 shows the complete diagram of connections for the arrangement according to Fig. 294. The switch S_1 controls the generator circuit, S_2 the battery circuit; S_3 is a double-throw switch which makes connections for charging or discharging. For charging the battery, S_3 is thrown to the right, and the switches S_1 and S_2 are closed. The charging current flows from the positive terminal of the generator, through S_3, to the charging end-cell switch E_2; thence through the

battery, ammeter A_2, overload circuit-breaker CB_2, underload circuit-breaker CB_1, and switch S_2 to the negative terminal of the generator. At the same time, the line is supplied with current through the discharge end-cell switch E_1 and the ammeter A_1. The underload circuit-breaker is used in order to prevent the battery from sending current back into the generator. An underload circuit-breaker is installed only in such battery plants in which the load is varying slowly, so that there are distinct periods of charge and discharge. In railway installations the load is rapidly fluctuating, and the battery current is reversed, sometimes every few seconds: No underload circuit-breaker could be used under such conditions.

For discharging the battery into the line, in parallel with the generator, the switch S_3 is thrown to the left; this cuts the charging end-cell switch E_2 out of the circuit, while the underload circuit-breaker CB_1 is short-circuited by the lower blade of the switch S_3. The discharge is regulated by the end-cell switch E_1 and the field rheostat of the generator. On the other hand, if it is desired to shut down the generator, the switch S_1 is opened, and the battery continues to supply current alone. This is usually the case late at night and early in the morning, when the demand for current is quite small. If the switch S_2 is opened, instead of S_1, the battery is disconnected from the line, while the generator continues to supply the power.

V is a voltmeter which, by means of the voltmeter switch *V. Sw.*, can be connected so as to show at will: the generator voltage, the battery voltage, or the line voltage. In addition, a portable 3-volt instrument is always used in storage-battery plants, for measuring the voltage of each individual cell.

379. EXPERIMENT 18-D. — End-Cell Control of Storage Batteries. — The connections with a single end-cell switch are shown in Fig. 293; with a double end-cell switch in Fig. 294, or more in detail in Fig. 295. Try both systems in actual operation, under the conditions specified in § 377.

Report actual diagrams of connections and numerical results of the test. State voltage fluctuations with sudden variations of the load, and give the relative fluctuations of the current in the generator and in the battery. Figure out the number of points necessary on the single end-cell switch and on the double end-cell switch.

380. Floating Batteries. — In plants in which considerable voltage fluctuations are not objectionable, or are unavoidable, storage batteries are often used without any means for regulating them, simply as shown in Fig. 286. This allows the battery to be freely charged or discharged

with the fluctuations of the load. Such connections are used in some electric-railway substations, and also in plants containing cranes and elevators. The number of cells is selected so that, when the generators give approximately their full output, the voltage at the bus-bars is equal to the e.m.f. of the battery: under such conditions no current flows into or out of the battery.

When the load is below the average, the generator voltage is higher than that of the battery, and a charging current flows into the battery. When the generator is carrying a rather heavy load, its voltage drops below that of the battery, and the battery discharges into the line, helping the generators (or rotary converters, if it is a substation). With such an arrangement, the generator load is more constant than without the battery. The battery is never entirely discharged or fully charged, but is maintained in a medium condition. Once every few weeks it is necessary to raise the generator voltage and to give the battery a thorough charging, and even an overcharge, in order to prevent the formation of lead sulphate.

Such a *floating* battery is more effective the wider the voltage fluctuations. The voltage at the end of the feeders varies much more than in the substation, on account of the ohmic drop in the feeders: therefore, it is better to have a floating battery at the end of the line. The advantages are: The average voltage being lower than in the substation, less cells are required; the fluctuations of the voltage being more pronounced, the battery is charged and discharged within wider limits; the load on the generators or rotary converters is steadier; there is a considerable saving in line copper, since the feeders have to carry an average current only, instead of the maximum current. The chief disadvantage of placing the battery at the farther end of the feeder is that extra room and attention are required outside the substation.

381. EXPERIMENT 18-E. — Performance of Floating Batteries. — Connect a battery in parallel with a shunt-wound generator, as in Fig. 286, and select such a number of cells that the battery neither charges nor discharges at a desired load. The line must have a considerable resistance so as to represent the actual conditions of railway service; the resistance being such as to give from 10 to 15 per cent voltage drop at full load. The load, representing street cars, is connected at the further end of the line. Have an ammeter in the generator circuit, and one in the main line; and connect a voltmeter so as to measure, at will, the voltage across either end of the line.

(*a*) First disconnect the battery and use the generator alone, increasing the load from zero to a heavy overload without regulating

the field rheostat. Measure line amperes and the volts at each end of the line.

(*b*) Apply the same values of load with the battery and the generator working in parallel. Observe the proportion of the load taken by the battery, and the improved conditions of voltage regulation. If the results show that the battery is charged more than it is discharged, add one or more cells, and vice versa. Repeat the experiment, until the battery gives the best performance, in other words, keeps the generator load as steady as possible.

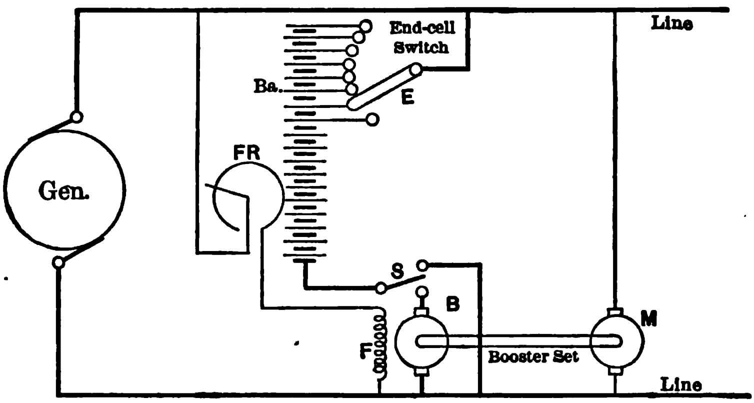

FIG. 296. Battery charged by a non-automatic booster, and discharged through an end-cell switch.

(*c*) Put a few turns of series winding on the generator field, but not enough turns to make the machine flat-compounded. Observe the difference in the performance of the battery and the new voltage regulation.

(*d*) Connect the battery at the farther end of the line and repeat the same runs, viz.: Investigate the influence of the resistance of the line, of the position of the load, and of compounding the generator.

Report. Give results in such form as to show the relative usefulness of the floating battery under the various conditions investigated.

BATTERY BOOSTERS.

382. With the exception of smaller plants in which storage batteries are charged in parallel, or by means of an end-cell switch, most storage-battery plants are provided with so-called *boosters*, or extra generators for regulating the charge (and sometimes also the discharge) of the batteries. The simplest combination is shown in Fig. 296: The booster

B is direct-driven by a shunt-motor M; the armature of the booster is in series with the battery; the fields F are separately excited across the bus-bars; E is the end-cell switch.

When the battery is discharging, the switch S is thrown up so that the booster is cut out of the circuit; the discharge is regulated by the end-cell switch E. For charging the battery, the switch S is thrown down and the booster e.m.f. raised by means of the field rheostat FR; thus giving, together with the generator pressure, a voltage sufficient for charging. This voltage is regulated, as the charge progresses, by means of the same rheostat FR. Instead of using an end-cell switch, the same booster may also be used for regulating the discharge of the battery. In this case a reversing switch must be connected into its field circuit, so that the direction of the induced e.m.f. may be changed. Some companies connect the booster field across the battery, and not across the line, as in Fig. 296; there is little difference between the two methods.

Shunt-excited boosters with hand regulation are satisfactory only in plants in which the load varies gradually and regularly, so that the battery can be charged and discharged during considerable periods of time. In railway service, where the load fluctuates within wide limits, and where charge and discharge sometimes follow each other every few seconds, it becomes necessary to have *automatic* boosters whose e.m.f. is added to or subtracted from that of the battery, according to the magnitude of the load.

Two types of automatic boosters are used at present: (*a*) *Differential boosters*, in which the booster field is varied by the addition of compounding windings (Fig. 297); (*b*) *Relay boosters*, in which the current in the shunt field is regulated by suitable relays (Figs. 299 and 302).

383. Differential Booster. — This belongs to the first of the two types of automatic boosters mentioned above, and is shown in Fig. 297. It differs from the non-automatic booster (Fig. 296) in that the end-cell switch E is omitted, and the booster is provided with an additional series-field winding F_2, which opposes the action of the winding F_1. At a certain average load, F_1 and F_2 neutralize each other, and the booster e.m.f. is $= 0$. At this load the generator voltage must be made equal to that of the battery, so that the battery neither charges nor discharges. At a heavier load the action of F_2 is stronger than that of F_1, and the booster e.m.f. is added to that of the battery, assisting its discharge. On light loads the action of F_1 is stronger than that of F_2, and the booster tends to send a charging current into the battery. This action is entirely automatic, and the

booster tends to maintain a constant load on the generators, the battery taking up the load fluctuations.

Experience shows that in order to have this system work satisfactorily, it is necessary to add a third field winding F_3 (shown by dotted lines), acting in the same direction as F_2. This winding automatically corrects the voltage of the booster for the state of charge of the battery, in the following way: Suppose that the currents in the three field windings are so adjusted, that the booster e.m.f. is zero with the rated generator current and with the battery partly discharged. Then, with the same load and with the battery fully charged, the battery tends to take more than its share of load, reducing the generator current. This reduces the current in the differential winding F_2, and gives a preponderance to the shunt field of the booster. An e.m.f. is produced in the booster such as to oppose the e.m.f. of the battery and to prevent it from discharging.

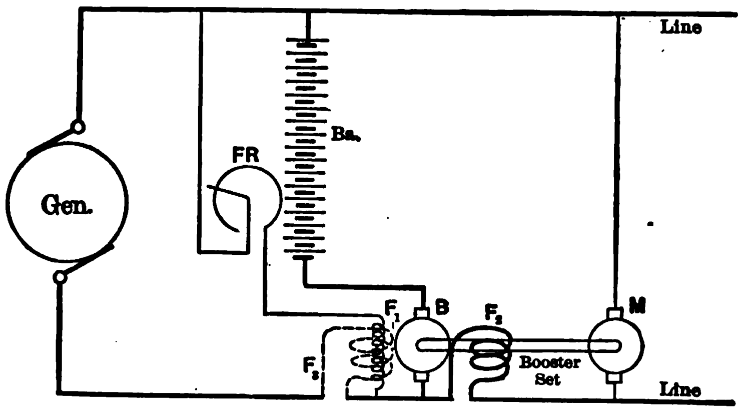

FIG. 297. Automatic differential booster.

On the contrary, when the battery is nearly discharged and does not take its share of load, the generator becomes overloaded. Then an excessive current flows through F_3 and boosts the battery voltage helping its discharge. In this way the winding F_3 helps to keep the generator load constant.

384. EXPERIMENT 18-F. — Performance of Storage Batteries Controlled by Shunt-Wound and Differential Boosters. — Connect a non-automatic booster, as shown in Fig. 296. Have an ammeter in the line and one in the generator circuit; the battery current is, at any moment, the difference of the two ammeter readings. Operate the set under the conditions specified in § 377. To represent voltage changes

in the battery, that depend on the state of its charge, one or more cells may be disconnected, or more cells added to the battery. Some resistance may also be used in series with the battery, to imitate an increase in internal resistance. Add a reversing switch in the booster field and try to regulate discharge by the booster, instead of by the end-cell switch.

Take a differential booster, shown in Fig. 297, first with both windings F_2 and F_3 in the line circuit, then with the same windings connected as shown in the sketch. Compare the two arrangements with regard to their ability to maintain a constant generator output. Adjustments for the best regulation are made by the booster shunt-field rheostat, and by placing shunts around the series windings.

385. Carbon-Pile Booster Regulator. — One common disadvantage of automatic boosters with series fields, as shown in Fig. 297, is that the booster itself becomes quite large and expensive, since its

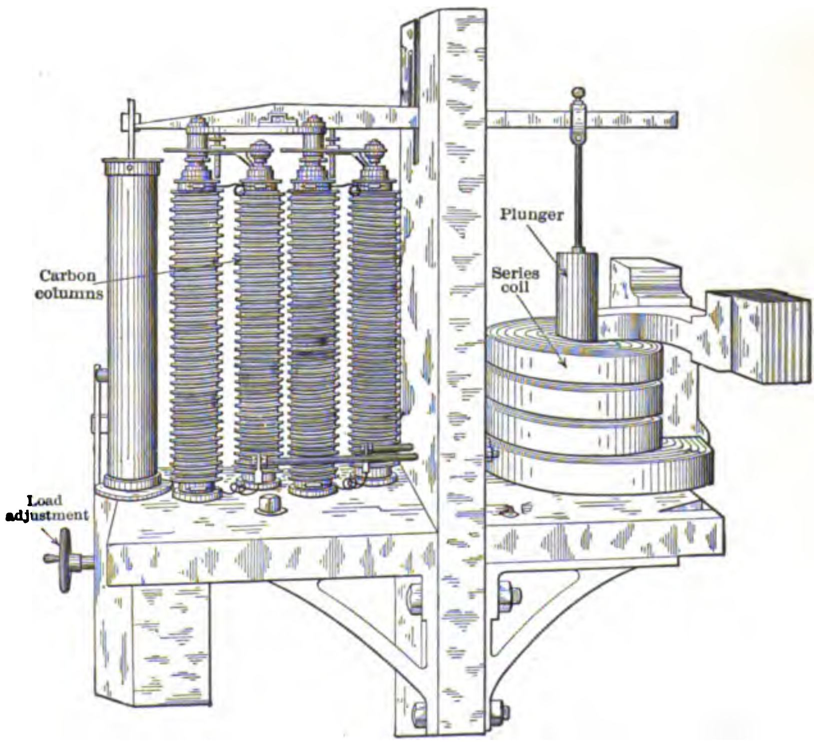

FIG. 298. Carbon-pile battery-regulator (The Electric Storage Battery Co.).

frame has to accommodate three field windings. It has been sought, therefore, to have on the booster only the shunt winding, as in Fig.

296, and to provide *outside the booster* an additional device that would automatically vary the magnitude and the direction of the current in

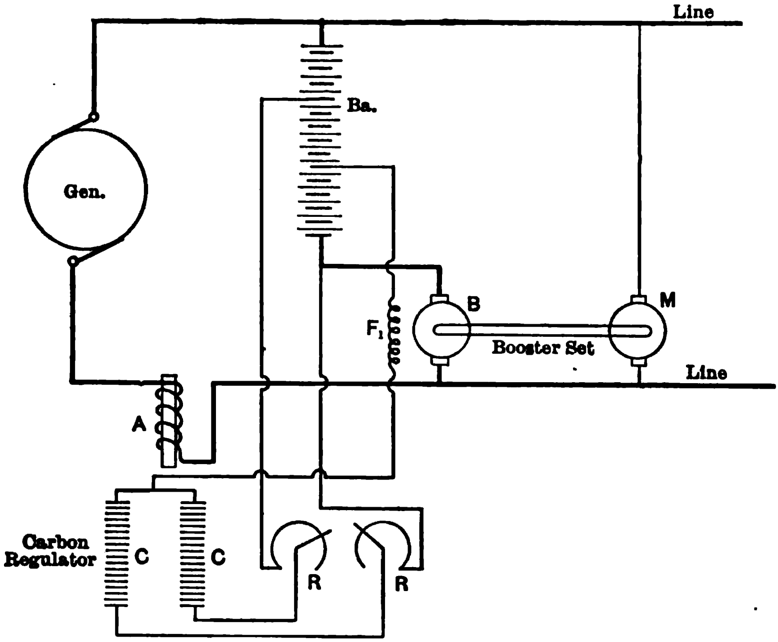

FIG. 299. Electrical connections of a booster, controlled by a carbon-pile regulator.

this shunt winding, according to the load. A device of this kind, the so-called *carbon-pile regulator*, is shown in Fig. 298; Fig. 299 shows the

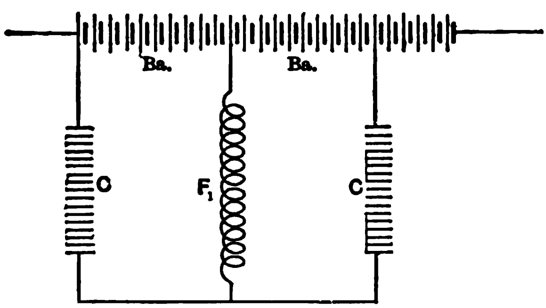

FIG. 300. A simplified diagram of connections between the booster field and the carbon regulator.

electrical principle on which it is based. The regulator is usually mounted on the main switch-board.

Generator current, instead of passing through a series winding placed on the booster, passes through the solenoid A of the regulator. An iron core, actuated by this solenoid, compresses more or less, through a suitable leverage, two sets of columns CC consisting of carbon disks. These carbon piles are connected to the booster field and to the battery, as shown in Figs. 299 and 300. The resistance of the piles consists chiefly of the contact resistance between the disks, and therefore varies within wide limits, with variations in the pressure exerted by the core of the solenoid A.

With the normal value of the generator current, the pressure on both piles is the same; their resistances are equal, and no current flows through the booster field F_1. The whole arrangement resembles the familiar Wheatstone bridge scheme, in which the booster field takes the place of a galvanometer. When the current is below or above normal, one column is compressed more than the other, the bridge is not balanced, and a current flows through the booster field in one or the other direction, causing the battery either to charge or to discharge.

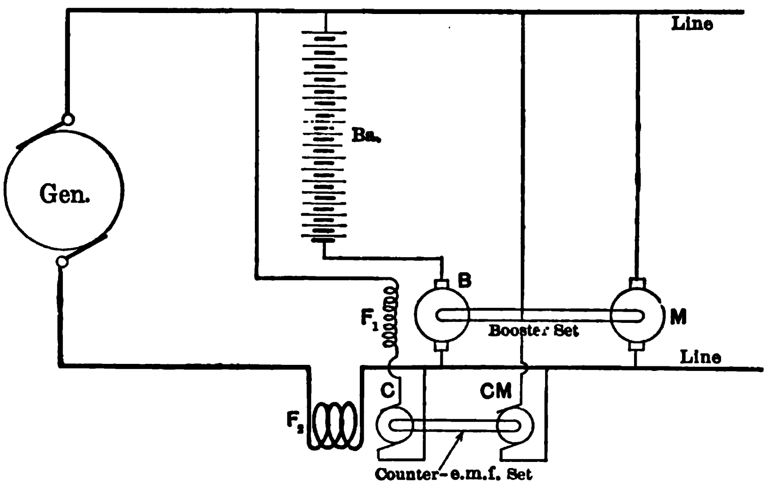

FIG. 301. Automatic booster controlled directly by a counter-e.m.f. machine.

The arrangement is entirely automatic in its action, and takes the place of a booster with two or more field windings, tending to keep the generator current constant.

In reality the connections are more complicated than those shown in Fig. 299: It would be too wasteful to have a current circulate all the time through the carbon columns, especially of such a magnitude as to be sufficient to energize the booster fields through mere unbalancing

of resistances. Therefore, except in very small installations, *the carbon regulator actuates the field of a separate exciter, which in turn supplies current to the field of the booster.* The exciter being a much smaller machine than the booster, considerably less energy is lost in the regulator. The booster and the exciter are usually mounted on the same shaft and driven by a direct-connected motor.

The carbon-pile regulator is used by the Electric Storage Battery Company, chiefly in large railway plants.

386. Booster Regulation by Counter-E.M.F. — Another relay arrangement is shown in Fig. 301. Here the booster field F_1 is automatically regulated by a small counter-e.m.f. machine C. The field F_2 of this machine is excited by the main current, similarly to the

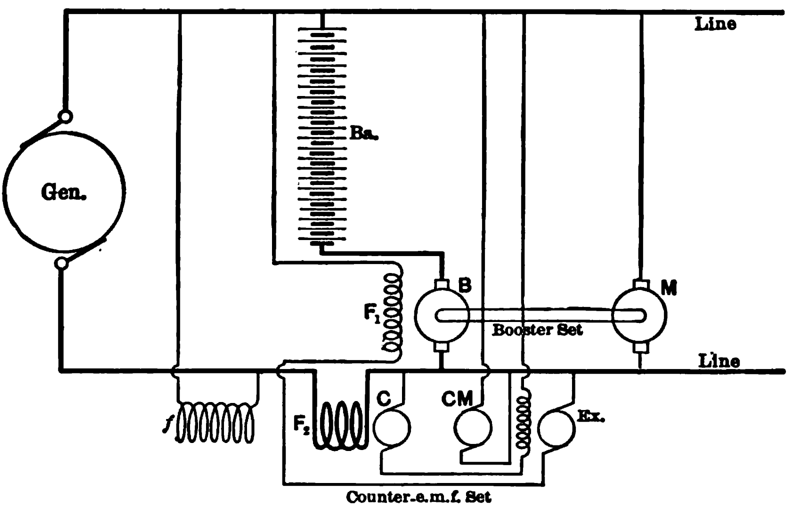

FIG. 302. Automatic booster controlled by a counter-e.m.f. machine, through an exciter (The Gould Storage Battery Co.). See Note on p. 424.

solenoid A shown in Fig. 299. At a certain desired value of this current, the counter-e.m.f. of the machine C can be made such that no current will flow through the booster field F_1. When the generator current is below this value, the booster field is excited in such a direction that the battery is charged, and vice versa.

Formerly the machine C was direct-connected to the main booster set and driven by the same motor. Experience showed, however, that the size of this machine can be considerably reduced by driving it separately, at a higher speed, by a small motor CM.

The size of the counter-e.m.f. set is still more reduced by introducing

a second relay machine, as shown in Fig. 302. Moreover, this arrangement increases the sensitiveness of regulation, and permits the counter-e.m.f. sets to be made of the same standard size with widely different sizes of batteries and boosters. The scheme shown in Fig. 302 is the one used by the Gould Storage Battery Company.

The counter-e.m.f. machine C, instead of acting directly on the booster field, as in Fig. 301, acts on the field of a small exciter *Ex.*, which in turn controls the booster field current. The armature of the counter-e.m.f. machine is connected in series with the exciter field, across the main bus-bars. When a normal current flows through the main generator, and consequently through the field F_2, the voltage induced in the armature C just balances the voltage across the bus-bars; no current then flows through the exciter field, and the booster excitation is $= 0$. When the generator current is above normal, the voltage in C is higher than that across the bus-bars, and the exciter field is energized in such a direction as to assist the battery to discharge. The opposite takes place when the generator current is below normal. With proper relations, the system works so as to keep the generator load practically constant.

In some cases, the counter-e.m.f. machine has an additional field winding connected across the line and giving a constant excitation. The addition of this winding makes the system more flexible and permits of an adjustment for any desired performance of the battery. Further adjustment is made possible by a rheostat in series or in parallel with the field winding F_1, and also by shunting the main series-winding F_2 by adjustable resistances. See Note on p. 424.

387. Vibrating-Contact Booster Regulator. — The success of the Tirrill regulator (see §§ 231 and 325) for controlling voltage in generators, led to the idea of applying the same principle to storage battery regulation. Such a battery regulator with vibrating platinum contacts has been developed by the Westinghouse Electric and Manufacturing Company. In common with the systems described in §§ 385 and 386, the booster field is energized either for charge or for discharge by a separate exciter. The same exciter, which may be either direct-connected to the booster set or driven by a separate motor, has two equal and opposite field windings, which we shall denote by A and B, connected in parallel across the main bus-bars; a third field winding C is connected across the armature terminals of the exciter and is its regular shunt winding.

A platinum contact, actuated by the main generator current, short-circuits a resistance in series with either A or B and makes the action of one of the differential windings predominant. The shunt winding

C immediately begins to build up the exciter current, which in turn effects the desired booster regulation. The tendency to over-regulate is checked by an electromagnet which immediately opens the platinum contact.

The details of the regulator are as follows: An ammeter shunt is inserted into the generator circuit, so that the drop across the shunt is proportional to the generator current. A regular milli-voltmeter movement, consisting of a moving coil, a permanent magnet and a spiral spring, is connected across the shunt. We shall denote this milli-voltmeter No. 1. Another similar movement No. 2 is connected across the booster field; the arms of the two moving coils have two platinum tips which correspond to the main contacts in a Tirrell regulator. The closing or opening of these contacts causes an electromagnet to short-circuit one or the other of the above-mentioned resistances in series with the exciter fields.

Suppose the main contact between the two moving coils be closed; this closes the auxiliary contact which energizes the booster in such a direction as to help the battery to discharge. As soon as the exciter voltage begins to build up, the movement No. 2 opens the main contact. The auxiliary contact is also opened, and returns to its zero position in which it builds up the booster field in the opposite direction, i.e., for charging the battery. This increases the generator current above normal, the main contact is closed again, etc.

In reality, both contacts are vibrating continually, and in this way maintain the generator current practically constant.

For small adjustments, the spiral spring of movement No. 1 may be tightened or loosened. For larger steps a series of resistances are provided with plugs by which the drop across the ammeter shunt is increased or decreased. Movement No. 1 is also provided with a sensibility weight. By shifting it, the regulator may be over-compounded; this means that when the external load increases, the generator load also increases by a desired percentage.

388. EXPERIMENT 18-G. — Performance of Relay-Operated Boosters. — The experiment comprises any of the systems described in §§ 385 to 387. Wire up the arrangement available for test and operate it under various conditions specified in § 377. Pay particular attention to current and voltage fluctuations when the load varies suddenly, and determine the limits within which load and voltage may be kept constant. Try the various adjustments possible with the regulator under test, and see if the generator current may be made to follow, to a certain degree, load fluctuations. Investigate regulation

with a slightly different number of cells; this would correspond to the case when the battery is fully charged or totally discharged.

A mature judgment is expected of the student in the performance of this experiment. The electrical connections are rather complicated, and the various parts of the system are very closely interdependent. Therefore the connections must be made with an extreme care, and properly labeled; where possible, the separate machines entering into the system must be run separately, to see that the connections are correct, and that the machines operate properly. There is a tendency on the part of some students to concentrate their attention upon the readings rather than upon the general character of the performance of the machines under test. In this particular case, it is this *general performance and the possibilities of the system* under various practical conditions that are of paramount importance.

Report. Draw a complete diagram of connections for the system investigated, with all switches, fuses, measuring instruments, etc.; write concise instructions for starting and operating the installation. State the character of regulation obtained and per cent fluctuations from the rated current. Give your criticisms, if any, of the system.

389. Storage Batteries in Alternating-Current Plants. — The question of equalizing load in large alternating-current power plants, by means of storage batteries, gains more and more in importance. At present, batteries used in large railway and lighting plants are usually installed in substations; each substation is thus regulated separately. A better economy could be obtained by having one large battery in the generator station, even though it would necessitate extra rotary converters, or motor-generators between the line and the battery.

With fluctuating loads, such batteries have to be controlled by automatic boosters with some relay arrangement between the alternating-current line and the booster field. The requirement in most cases would be to regulate for constant kw. generator output; the current then varying only with power factor.

The problem is in rather an experimental stage, though it would seem that the systems of regulation described in §§ 385 to 387 may be made to operate successfully with alternating currents.

The Westinghouse regulator (§ 387) is particularly promising in this respect, as the only change would be to replace the ammeter shunt and the milli-voltmeter movement No. 1 by a suitable wattmeter movement. The Gould arrangement shown in Fig. 302 has also been successfully applied to alternating-current plants, by exciting the field F_2 from the main line through series transformers and a special recti-

fier. The device is adjusted so as to rectify only the working component of the current, thus making the effect of the booster depend on watts output and not on line amperes. A second rectifier, suitably displaced from the first, may be used for the wattless component of the current; this component, when rectified, may be used for compounding the rotary converter, in order to correct for the power factor of the load.

NOTE TO § 386. The set in use in Cornell University differs from that shown in Fig. 302 in that the field f is connected in series with the armature C and with the exciter field. The field F_2 is connected in parallel with adjustable shunts.

CHAPTER XIX.

MOTOR STARTERS AND REGULATORS.

390. THE purpose of this chapter is to acquaint the student with the simplest forms of motor starters and speed regulators used with direct-current motors. More complicated devices of this kind, known as controllers, are described in Chapter XXXIII. Electric railway controllers are described in Chapter XXXIV. For a description of induction motor starters and regulators see §§ 335 and 336.

Small electric motors are used in all kinds of industrial establishments and are usually operated and taken care of by persons with limited electrical training. It is, therefore, necessary to provide such motors with starting and regulating rheostats designed specially to meet the severe conditions of usage.

One fundamental requirement, which every motor starter must satisfy, is that *its resistance must not remain short-circuited when the main switch is opened, or when the power is off.* Should the power be " on " again, or should the main switch be carelessly closed, without first connecting the resistance " in," the fuse is sure to blow out. In some cases serious damage may be done to the motor, or to a measuring instrument in the circuit. Therefore, all starters used for commercial work are provided with an automatic release which cuts the starting resistance " in," when the power is off, or when the main switch is opened. The starting rheostat is sometimes combined into one device with a circuit-breaker, which opens the motor circuit in the case of an overload. Where speed control is required, the starter and the field rheostat are usually combined into one apparatus, with the parts so interlocked as to make it impossible to start the motor with a weakened field.

391. Starters with No-Voltage Release. — A common type of starter for shunt-wound motors is shown in Fig. 303, in front and side views. Its automatic feature consists in an electromagnet (no-voltage release) which holds the starting arm in the running position as long as the coil is energized from the line. Should the main switch be opened, a fuse blow, or the power be shut off for any reason, the starting arm is released, and returns to its " off " position under the action of the spiral spring at its pivot.

The starting resistances are placed in a box provided with ventilating slots. Taps from resistances are taken to the contact buttons on the face plate. The release coil is wound on an iron core, and is provided with two pole-pieces. The starting arm has an iron armature attached to it, which is held by the pole-pieces in the running (extreme right) position of the arm.

The armature of the motor is connected across the circuit in series with the starting resistance. The field and the release coil form another circuit. When the motor is standing still the starting arm is in the position shown in the sketch, and the main switch is open.

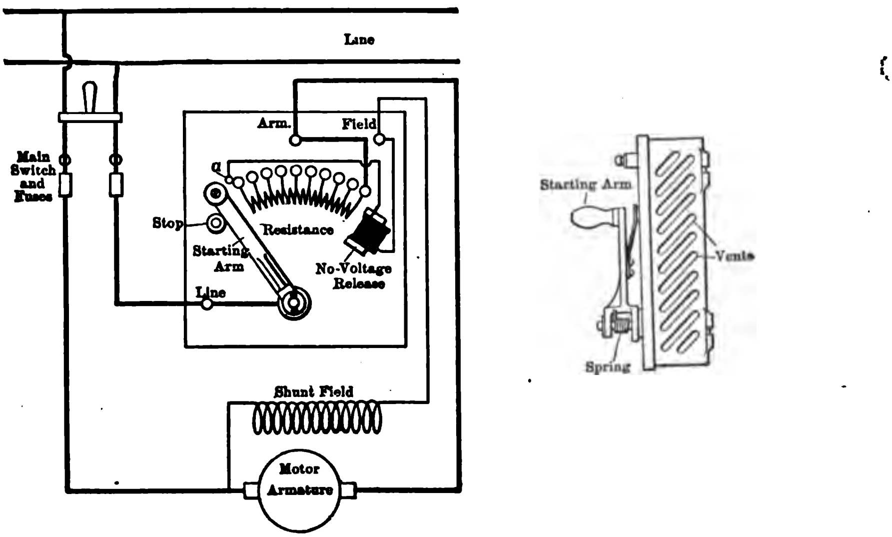

Fig. 303. Motor starter with no-voltage release.

To start the motor, the main switch must be closed first, and then the starting arm moved slowly to the right. On the first notch all of the starting resistance is connected in series with the armature; as the arm is moved farther, the resistance is gradually cut out of the circuit, until on the last notch the armature is connected directly across the line. In this position the starting arm is held by the release electromagnet.

To stop the motor the main switch is opened. This deënergizes the release coil, and the starting arm flies back to its zero position, under the action of the spiral spring, seen in the side view to the right. The same happens, should the field circuit be open for any reason, or the power be shut off. Thus, whenever the motor is stopped, the

starting resistance is *automatically* introduced into the motor circuit, protecting the motor for the next starting.

The small auxiliary contact *a* connected to the first starting button serves two purposes: (1) It permits energizing the field of the motor a moment before the armature circuit is closed, thus allowing for the time lag due to a considerable inductance of the field winding. (2) It takes up the spark when the starting arm flies back to zero position; after the contact is sufficiently burnt by this spark, the button *a* can be easily replaced.

It will be seen from the diagram that the part of the starting resistance cut out of the armature circuit is automatically introduced into the field circuit. This is of no practical importance, since the starting resistance is many times lower than the resistance of the field winding of the motor.

In some cases, the motor field winding and the no-voltage release coil are connected independently across the line, instead of being in series with each other. This is done, for instance, when it is impossible to put the required number of ampere-turns on the coil in any other way, especially with high voltages.

In the above starting box the arm is returned to its zero position if it be left on an intermediate notch, so that the starter cannot be used for regulating the motor speed. In some cases, however, this regulation is required, and the starting arm is allowed to remain indefinitely in any position. For instance, regulators used with small fan motors, where economy is a secondary consideration, are so arranged.

If it is desired to have a no-voltage release with such regulators, the starting arm is provided with a sector having slots on its periphery. The release coil has a pivoted armature carrying a hook on one end. This hook engages in any of the slots of the sector, and holds the arm in a desired position, as long as the coil is energized. When the power is off the armature is released and the spiral spring returns the arm into the "off" position.

392. Multiple-Switch Starters. — With large motors it becomes difficult to insure a good contact between the buttons and the arm, with the construction shown in Fig. 303. A good solution is to use separate switches for each step, as shown in Fig. 304. The connections are similar to those shown in Fig. 303, including the automatic no-voltage release. The switches are mutually interlocked, so that they can be closed in a certain order only. The first switch to the left, when closed, is held in position by the no-voltage coil, provided the latter is energized. This first switch pushes out of the way a stop

which otherwise prevents the second switch from being closed. Now the second switch may be closed; this being done, the stop of the third switch is lifted up, etc. Should the power be cut off, the no-voltage coil releases the first switch, and then all the switches open at once.

Some details of construction may be seen in the side view to the right. The switch s_1 is shown closed, the switch s_2 open. The switches are provided with curved copper brushes c which close the circuit between a bus-bar n and contacts m, connected to the sections of the starting resistance. The retaining hooks d and their locks are also clearly seen in the sketch.

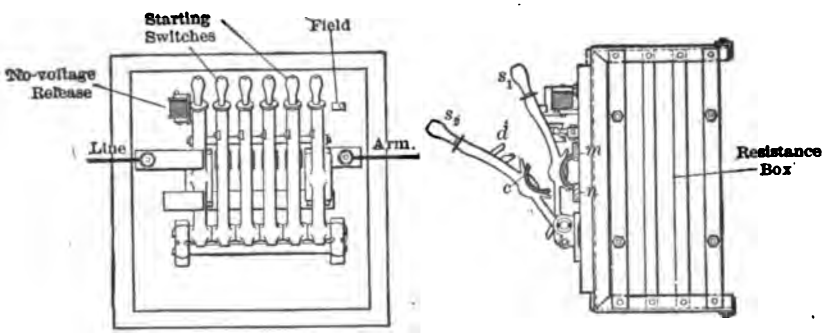

FIG. 304. Unit-switch type motor-starter with no-voltage release.

393. Electrically Operated Starters. — Instead of operating a starting-rheostat by hand, as shown in Figs. 303 and 304, the rheostat may be operated electrically, by solenoids energized from an auxiliary circuit.

The principal cases in which starters are operated electrically (Fig. 305) instead of by hand are:

(1) Where it is necessary to start a motor from a distance, for instance, from an elevator car.

(2) Where it is desired to have an acceleration independent of the operator's will, as in large electric cars.

(3) Where the motor is started and stopped automatically, — for instance, by a float in a water tank.

With the arrangement shown in Fig. 305, closing the main switch energizes the solenoid, whose plunger moves the starting-arm upward, cutting out the resistance. The rate at which the arm is moved is regulated by the dash-pot. At the end of the travel, an auxiliary contact shown in the sketch is broken by the arm, and some resistance, usually a lamp, introduced into the solenoid circuit. The current in

the coil is thereby reduced to a value just sufficient to hold the starting-arm in the upper running position. When the power is off, or the main switch is opened, the solenoid is deëner-gized, and the starting-arm falls by gravity to its zero position.

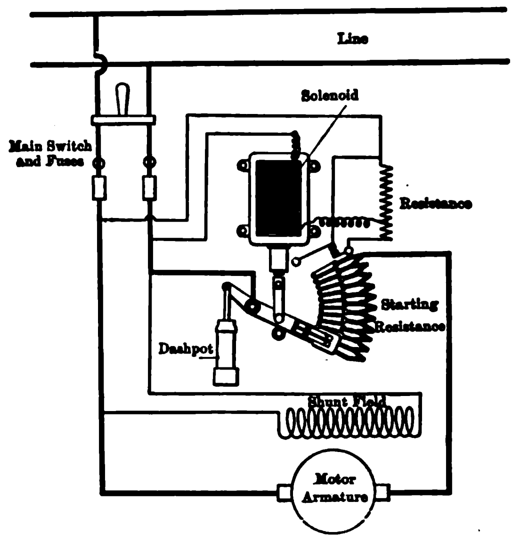

FIG. 305. An automatic motor starter.

It is not necessary to run the main line to the place from which the motor is started: An electrically operated main switch, Fig. 306, may be placed near the solenoid starter, and only small service wires run to the operator's place. Closing the service switch energizes the solenoid *C* of the main switch, which in turn closes the main circuit. This energizes the starter solenoid and the starting-arm begins to move (Fig. 305).

This arrangement is used with motor-driven pumps and air com-

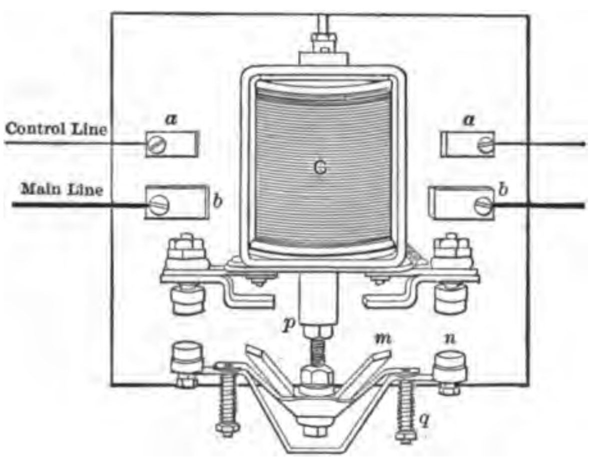

FIG. 306. An electrically operated switch for remote control.

pressors. The circuit *aa* to the solenoid of the main switch is closed

automatically by a float switch, or by a pressure indicator, when the water level in tank or the air pressure is beyond certain limits. This automatically starts and stops the motor, as needed.

With large motors, or when the connections are more complicated, several unit switches, such as the one in Fig. 306, are used, instead of a starting-arm. This is the system applied in many electric elevators (see Fig. 501); also in the multiple-unit system of electric train control (Fig. 512), and in the electric drive of steel mills.

394. EXPERIMENT 19-A. — Operating Direct-Current Motor Starters with No-Voltage Release. — A starting-box should be provided, of a type shown in Fig. 303, and a suitable motor to be operated in connection with it; also an ammeter, a voltmeter, and means for loading the motor.

(1) Wire up the motor and the starting-box, and practice starting and stopping. Make clear to yourself the order in which the main switch and the handle of the rheostat should be operated, and to what extent the arrangement is "fool-proof"; also what would happen if operations were performed in a wrong order.

(2) Explain why the handle does not fly back immediately after the main switch is opened; prove the explanation by an experiment. Determine the minimum line voltage at which the coil can hold the arm. Interpose pieces of thin paper between the coil and its armature, and observe the effect on the magnetic attraction.

(3) Apply a certain brake load and start the motor by moving the rheostat arm at a certain definite speed, for instance, using a metronome. Read instantaneous values of line amperes and volts across the armature every few seconds. With three observers, after some practice, it is possible to take readings on an instrument every two seconds: One man signals at the proper time, another reads aloud the scale indications, the third records the readings. A much better way is to use high-speed recording ammeters and voltmeters (§§ 52 and 713), if such are available. Repeat the same experiment with different rates of starting, and with different values of the load.

(4) Measure total resistance of the starting-box, and the resistances of separate steps. This may be done by putting a steady current through the rheostat, and taking voltage drop between adjacent buttons.

(5) If electrically operated starters are available, such as shown in Figs. 305 and 306, connect up and operate them, in order to clearly understand their action. Take a few readings, as before, in order to characterize the devices by their performance.

Report. Draw diagrams of actual connections used during the experiment. Explain your findings concerning the operation of the no-voltage release coil. Give curves showing the variation of motor volts and amperes during the period of starting; show the influence of the load and of the rate of starting. Plot the resistance of steps and the total resistance of the rheostat to steps as abscissæ; explain the reason for which the resistances of various steps are made different.

395. Overload Release. — In the above-described starters, no provision is made for protecting the motor against overloads, except the fuses in the main circuit. This is a satisfactory solution in cases where overloads occur but seldom; but, with frequent overloads, fuses are expensive and inconvenient. An automatic circuit-breaker is preferably used in such cases, in place of fuses, or in connection with them. A circuit-breaker is an automatic switch opened by a coil connected in series with the main circuit. When the current exceeds a certain limit, the coil attracts an iron armature, which trips and opens the switch.

Where a fuse and a circuit-breaker are used in conjunction, the fuse is supposed to take care of long but moderate overloads, while the circuit-breaker operates on sudden excessive overloads. A continual overload is certain to heat up and melt a fuse, but it may not give enough momentum to the armature of the circuit-breaker to trip it. On the contrary, a short but heavy overload may not melt a fuse but is able to communicate a considerable momentum to the armature of the circuit-breaker.

There is some demand for starters having an overload feature incorporated in them, instead of separate circuit-breakers or fuses. A device of this kind is shown in Fig. 307. In addition to the parts shown in Fig. 303, it has a second arm k, which closes the main circuit and is connected by a spiral spring to the starting-lever, so that the two arms are impelled towards each other. Under ordinary conditions, the overload lever k is prevented from flying up by a lock t, and thus keeps the main circuit closed between the jaw j and the starting-arm.

Should the line current exceed a certain limit, the series coil c, shown in the lower part of the starter, attracts its plunger upwards; the same strikes the lock t, releases the overload lever k, which opens the circuit. The lever has no handle attached to it, so that in order to return it to its former position and close the circuit, it is necessary to return the starting-arm to its "zero" position, and then start the motor again. This feature prevents starting the motor with the resistance cut out of the circuit. The underload or no-voltage release acts in the same way as in Fig. 303, and is independent of the overload feature.

The overload release may be made to operate at any predetermined current (within certain limits), by raising or lowering the plunger by the knurled head *r*. The setting is read in amperes on the scale.

Another type of starter with an overload release is shown in Fig. 308; only the lower part of the face plate is shown, the rest being identical with the construction illustrated in Fig. 307. The use of the second arm is avoided here. When the current exceeds a certain limit, the overload coil *c* attracts the iron armature *i*, which strikes and closes the auxiliary contact *p*. This short-circuits the no-voltage release coil, and the starting-arm flies back to "zero" position. The armature *i* may be set by means of the screw *r* to open the circuit at a desired value of the current.

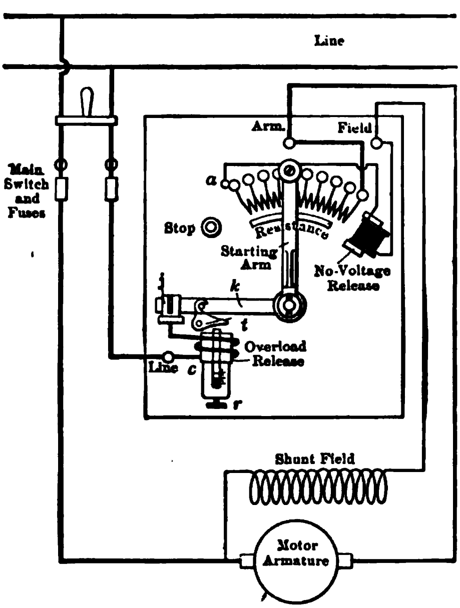

FIG. 307. A motor starter with no-voltage and overload release.

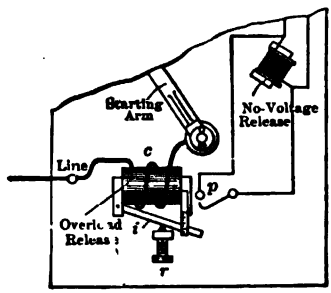

FIG. 308. Another type of overload release (see Fig. 307).

It is generally agreed that the device shown in Fig. 307 is more positive in its action than that shown in Fig. 308, but the latter is less expensive.

396. EXPERIMENT 19-B. — Operating Direct-Current Motor Starters with Overload Release. — Two types of starters should be investigated: (*a*) Double-arm starter, as in Fig. 307, and (*b*) single-arm starter, Fig. 308. It is well to test, in addition, an ordinary starter with no-voltage release (Fig. 303), using a separate overload circuit breaker.

(1) Connect the devices in succession to a motor, and practice starting. Observe the action of the overload protection. Make clear to

yourself that no wrong move is possible, except with deliberate intention.

(2) Calibrate the overload attachment in amperes. For this work use an ordinary load rheostat instead of a motor; the main current can be kept more constant.

(3) Make tests of the influence of the "time element" on the action of the overload attachment. Adjust a certain current through the coil *c*, and then increase the current by a certain per cent, first gradually, then instantaneously: observe the difference in the operation of the tripping mechanism. Perform this experiment with different values of current, and with different percentages of increase.

(4) Compare the action of fuses and of a circuit-breaker on slow and sudden overload; obtain, if possible, definite numerical results.

Report. Give a diagram of the actual connections used. Describe the influence of the time element, and the difference in the action of fuses and circuit-breakers. Give your opinion as to the relative advantages of the types of starters investigated, and describe peculiarities of operation, if any.

397. Field Control. — In the above-described starting rheostats, no provision is made for regulating the field current of the motor, in other words, for varying its speed. If speed control is required, an additional rheostat must be connected into the field circuit. But it must be remembered that the motor should always be started with as strong a field as possible, in order to get a good starting torque, without an excessive rush of current. Therefore, the starting and field rheostats must be suitably interlocked, either mechanically or electrically.

A popular device of this kind is shown in Fig. 309: the lower row of contacts is connected to the starting resistance, the upper row to the field rheostat. A double lever is provided, the outside arm being for the field contacts, the inside one for the starting contacts (see side view to the right). The outside arm only is provided with an operating handle. In starting, the two arms are moved together, but the field arm is electrically inoperative, because the field current flows directly through the starting-lever, the bar *b*, the solenoid, and into the field of the motor. At the end of the starting period, the starting-lever is attracted and held by the no-voltage release coil, while the field lever may be moved back to increase the speed of the motor. The upper row of contacts is now operative, since the starting-lever no longer touches the short-circuiting bar *b*, but rests on the blind button *d*.

Opening the main switch releases the starting-lever, which flies back, strikes on its way the field lever, and both levers are returned to the

"zero" position. It will be clearly seen from the above description, that it is impossible to start the motor with weakened field. An overload feature, such as is shown in Fig. 308, may be added to this starter.

In some cases it is preferred to have a field rheostat separate from the starter. In one device of this kind the field rheostat is kept normally short-circuited, by the armature of an electromagnet: This insures starting the motor with full field. The short-circuit is not removed by energizing this electromagnet, since the armature is too far from it to be attracted. But when the field-regulating arm is returned to its "zero" position, corresponding to the strongest field, it pushes the armature against the electromagnet, and removes the short-circuit. After this, any amount of resistance may be cut into the field circuit,

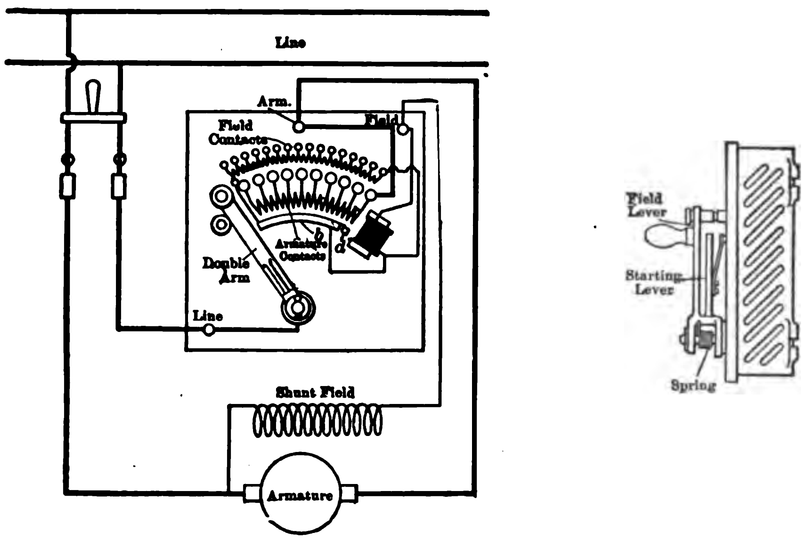

FIG. 309. A combination motor starter and speed regulator (Cutler-Hammer Mfg. Co.)

if desired, and the motor speed increased. But as soon as the main switch is opened, the short-circuiting armature of the field rheostat is again released and the field rheostat short-circuited, independent of the position of its operating arm.

398. EXPERIMENT 19-C. — Operating Motor Speed Regulators. — A device such as is shown in Fig. 309 should be provided; also an ordinary starter, as in Fig 303, with a separate field rheostat. An ammeter should be connected into the field circuit.

(1) Connect the speed regulator to a motor and practice operating it; make clear to yourself the automatic features of the device.

(2) Measure the speed and field current of the motor with several positions of the regulating handle.

(3) Measure the total resistance of the field rheostat, and the resistances of the separate steps; also the resistance of the motor field.

(4) Connect the common type of motor starter and a separate field rheostat in place of the combination starter and regulator. Devise an electrical or mechanical interlocking arrangement, which would prevent starting the motor with weakened field.

Report the connections used, and the automatic features of the device tested. Plot curves of motor speed, field current, and total resistance in the field circuit, to rheostat steps as abscissæ. Describe

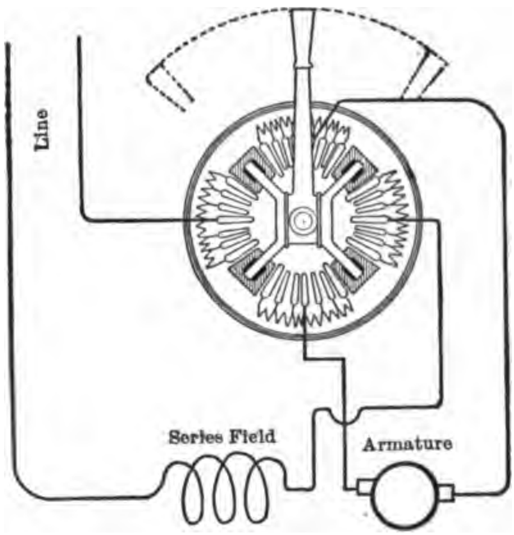

FIG. 310. Crane controller.

your own automatic arrangement, devised to prevent the motor from being started with weakened field.

399. Crane Controllers. — The principal points of difference between the duties which a crane controller is called on to perform, and those performed by the regulators and starters described above, are:

(1) Series motors are used on cranes, so that there is no separate field circuit (Fig. 213).

(2) No automatic feature or interlocking is required, the operator himself watching the performance of the motor constantly.

(3) The controller must be reversible.

Face-plate controllers (Fig. 310) are generally used for crane service. On large three-motor cranes. three such controllers are placed side by

side in the operator's cab: one for hoisting, one for transversal travel, and one for longitudinal travel. The connections may be easily followed in the sketch: The regulating lever is made in three pieces separated by strips of insulation; the two outside parts of the lever form a part of the circuit; the middle part is insulated therefrom.

The operation of the controller consists merely in the cutting in and out of resistances. Reversing is done by moving the handle in the opposite direction: this reverses the armature leads.

Blow-out coils (Fig. 509) are placed either on the contact arms or on the controller shaft. In the latter case, the iron of the framework is so disposed as to complete the magnetic circuit, and to give a blow-out action at the four points at which circuit is broken.

Only one half of the regulating resistances are used at a time; therefore one half of them may be omitted and the other half connected to both " forward " and " reverse " contacts. On the other hand, it is of some advantage to use separate resistances, because both of them work only half of the time, and have more opportunity to become cooled off.

400. EXPERIMENT 19-D. — Operating a Crane Controller. — Wire up a controller, as explained in the preceding article, and operate it in connection with a series motor. When operating a series motor, remember that it tends to run away when the load is removed (§ 251). To avoid this, either operate the motor at a voltage much lower than the rated voltage of the motor, or provide a brake load. A good precaution is to use an underload circuit-breaker, which opens the circuit when the current or the load falls below a desired limit.

A good arrangement of the test, and one that will give some insight into the requirements of crane service, is to make the motor actually lift a weight through the medium of a worm and a drum. Perform such measurements among those specified in §§ 394, 396, and 398, as are feasible in this case.

NOTE. For more complicated and special controllers see Chapters XXXIII and XXXIV, Volume II.

CHAPTER XX.

ELEMENTS OF TELEPHONY.

401. THE two most essential parts of every telephone apparatus are *the transmitter* and *the receiver*. Their construction and connections may be understood from the general scheme illustrating the trans-

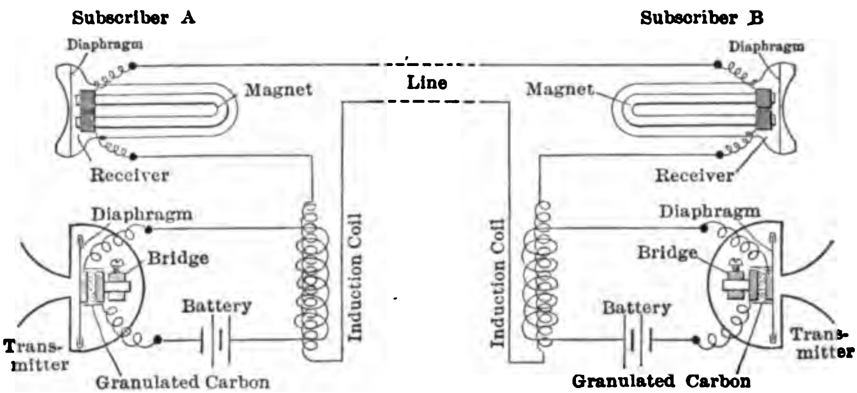

FIG. 311. Diagram illustrating transmission of speech.

mission of speech (Fig. 311); the sketch represents two subscriber stations connected by a line. The transmitter (Fig. 312) consists of a chamber filled with granulated carbon, between two carbon elec-

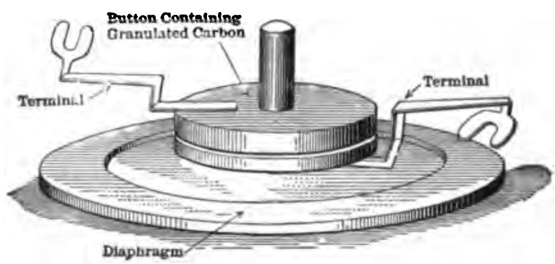

FIG. 312. Telephone transmitter.

trodes. The front electrode is fastened to a thin metal diaphragm; the back electrode is rigidly fastened to a metal bridge. The transmitter circuit is closed through a battery, as shown in Fig. 311. When

a person is speaking into the mouthpiece of the transmitter, and the sound waves strike the diaphragm, it is set in corresponding vibrations, and periodically compresses and releases the granulated carbon in the chamber. The resistance of the circuit is thus varied, and corresponding rapid variations occur in the current, giving the effect of small oscillating currents, superimposed upon current of a constant value.

These oscillating currents, acting through the induction coils, produce secondary currents which are sent through the line and reach the receiver of the other subscriber, where they are converted back into sound waves. The receiver (Fig. 311) consists of a sheet-iron diaphragm placed near the poles of a steel magnet. The poles are surrounded by coils of wire through which pass the incoming talking currents. These small variable currents change the magnetism in the pole-pieces and cause the diaphragm to vibrate accordingly, thus reproducing the

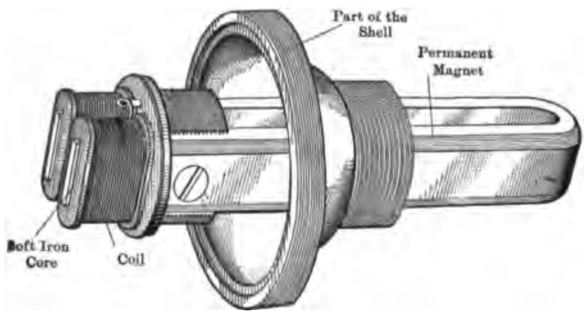

FIG. 313. Telephone receiver with the diaphragm removed.

sounds spoken at the sending station. A typical receiver is shown in Fig. 313: The magnet is made of *hardened* steel so as to retain its initial magnetism permanently. On the contrary, the polar projections are made of very soft iron, in order to respond more easily to small changes in magnetism.

402. Induction Coil. — Oscillating currents produced in the transmitter are sent to the line through the so-called *induction coil* (Fig. 311). This is merely a static transformer the purpose of which is (*a*) to raise the voltage of the "talking" currents, (*b*) to liberate them from the direct-current component. The purpose of raising the voltage is to effect a more efficient transmission through long lines. The direct-current is " sifted out," because it is useless in producing sound waves in the receiver, and should be confined to the local transmitter circuit.

A typical induction coil is shown in Fig. 314: It has a primary winding consisting of comparatively few turns, and a secondary winding of

many turns of very fine wire. The windings are placed in inductive relation one to another, on an iron core made up of fine iron wires, to prevent eddy currents. Such an induction coil differs from ordinary transformers, used in connection with light and power transmission in that its magnetic circuit is open, instead of being closed (compare Figs. 242 and 243). A closed magnetic circuit is not needed in telephonic transmission, on account of the very low magnetic densities used; it would be rather harmful, increasing hysteresis loss and distorting the speech.

In simple house telephones, where current is transmitted only a short distance, induction coils are sometimes omitted, and the transmitter connected directly to the line.

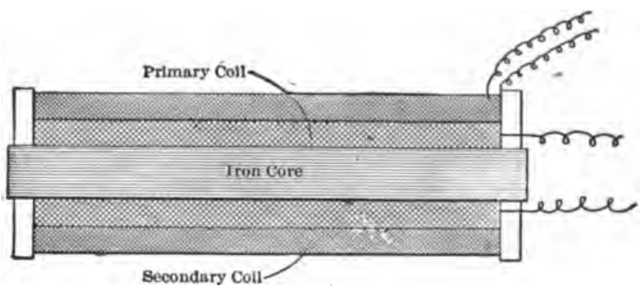

FIG. 314. Induction coil for telephone work.

403. EXPERIMENT 20-A. — Adjusting Transmitters and Receivers. — The purpose of the experiment is to afford familiarity with the construction and operation of the two most important parts of telephone apparatus — receiver and transmitter (§ 401). A special transmitter and a receiver should be provided for this purpose, arranged so that they can be easily taken apart, for study and adjustment. The transmitter is adjusted by varying the amount of the granulated carbon, the quality of carbon, and the pressure on it. In addition to this, the quality of speech depends on the magnitude of the current flowing through the instrument.

The receiver is adjusted by varying the distance between the pole pieces and the diaphragm. A well-adjusted receiver should be used for listening, while the transmitter is being adjusted, and vice versa.

Report. Draw sketches showing cross-sections of the instruments used for study and adjustment. Give your results with regard to the adjustment of the devices, and the factors affecting the quality of speech.

404. Classification of Telephone Installations.—Telephone installations differ widely in the number of subscribers served, and in the

distance through which speech is to be transmitted. The following general subdivision indicates the principal cases met with in practice.

(1) House, and intercommunicating telephones, used in residences, schools, offices, etc.: Such installations contain but comparatively few instruments, and these are connected at will by the subscribers themselves, without any operator.

(2) Private branch-exchanges, installed in large offices, factories, hotels, etc., where instruments are interconnected by an operator, and may also be connected for conversation with the city and long-distance telephone systems.

(3) City and long-distance telephone systems, covering many miles and serving possibly hundreds of thousands of subscribers.

Telephone installations may also be divided into those using local batteries, and into central-energy telephones. This latter distinction may not be important from the standpoint of the subscriber, but it materially affects the construction and the connections in the system. In local-battery telephones the current necessary for operating transmitters is supplied by dry or wet batteries placed in each telephone set. In systems using central energy the exchange is provided with a large storage battery, from which the current necessary for conversation is supplied. Further distinction between these two systems is made clear in the course of the chapter.

405. Signaling. — In addition to a receiver and a transmitter, each telephone set must be provided with a device for signaling and being signaled. In small house-installations ordinary electric bells with push-buttons are used for the purpose: The bell is either connected to the transmitter battery, or, if the distance between the stations is comparatively great, a separate battery of a larger number of cells is used for signaling. Battery bells cannot be used for signaling over any considerable distance, and are replaced by alternating-current bells, or so-called ringers. Current for these ringers is supplied by special generators, commonly called magnetos, because their fields are supplied with permanent magnets instead of electromagnets. Such a magneto is placed in the exchange, and the operator uses it in calling up subscribers.

The method of calling Central is different for local-battery and central-energy telephone systems. In the first system, each telephone set is provided with a small magneto-generator. By turning the crank of the generator, the subscriber sends currents through the line to the so-called "drop" in the exchange. The drop shutter is released, displaying the subscriber's number; this calls to the operator's attention that the subscriber wishes to speak to her.

In central-energy systems the "central" is called up by simply taking the receiver off the hook. This closes the subscriber's circuit and lights up a small lamp, which calls the operator's attention to the fact that a connection is desired. Further details in regard to signaling are explained in the later sections of the chapter.

406. Ringer and Magneto.—An alternating-current bell, also called a ringer, or polarized bell, is shown in Fig. 315 to the left. It consists of a permanent magnet NS, one of whose poles is periodically strengthened and the other weakened, and vice versa, by alternating currents sent from the magneto-generator, shown to the right. This unbalancing of forces causes a soft-iron armature to vibrate periodically; a hammer attached to the armature strikes alternately two gongs and produces the ringing.

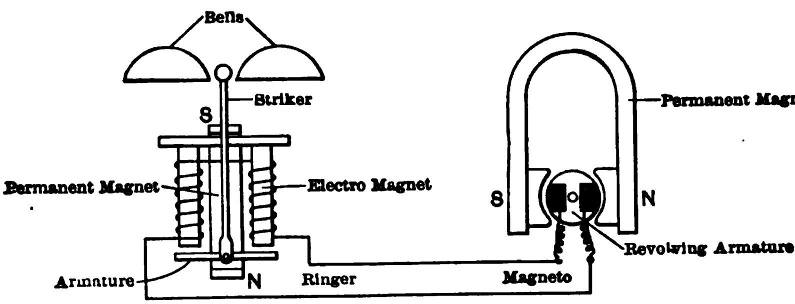

FIG. 315. Magneto-generator and polarized bell.

The generator, shown to the right, is a two-pole machine, with permanent magnets, and a shuttle-shaped armature. Magnetos in subscribers' sets and in small exchanges are hand operated, the speed being multiplied through gears: In large exchanges, ringing generators are usually driven by electric motors, and are running continuously; the operator merely connects the generator to the desired subscriber's line.

One detail in the construction of magnetos deserves to be mentioned: A magneto, connected across a telephone line, would shunt a part of the talking currents, and thus lower the efficiency of speech transmission. Therefore, magnetos are provided with some form of the so-called "generator cut-in," a device which keeps the armature circuit open, except when the crank is turned. These devices are based either on centrifugal force; or else, by turning the crank, the shaft is moved longitudinally and the contact is closed. In magnetos connected in series with the line the armature must evidently be normally short-circuited, except when in use. The devices used for short-circuiting

the armature are called "magneto shunts," and are based on the same two principles, mentioned above.

407. Magneto-Telephone Connections. — Standard connections in subscribers' sets, with local battery and magneto call, are shown in Fig. 316. The battery circuit is closed only when the receiver is off the hook: this is done automatically by the hook itself, which is therefore called the *switch-hook*. It is shown separately in Fig. 317: when the receiver is on the hook, the lower contact, connected to the ringing circuit, is

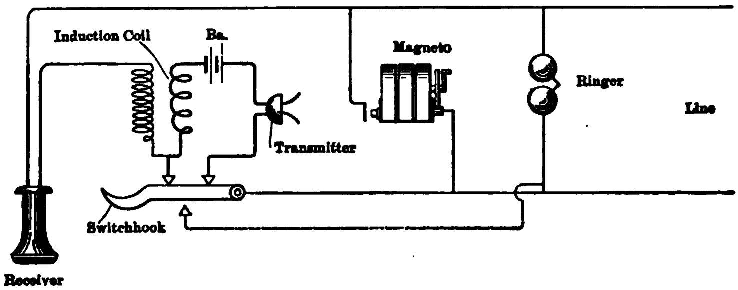

FIG. 316. Connections in a magneto telephone set.

closed, allowing the "central" to call up the subscriber. When the receiver is off the hook, the ringing circuit is open, while the upper contact, completing the battery circuit, is closed. With the connections according to Fig. 316, two contacts must be closed, when the receiver is off the hook. This is accomplished by adding one more spring and an extra contact to the switch-hook shown in Fig. 317.

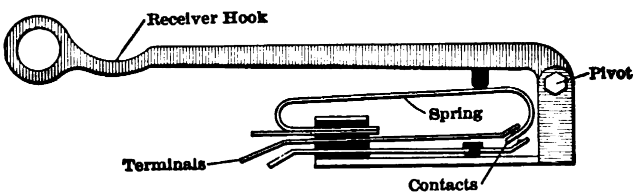

FIG. 317. Switch-hook

The ringer is sometimes left across the line all the time, in order to simplify the switch-hook connections. If the resistance and the inductance of the ringer are sufficiently high, only a very small part of the high-frequency talking current passes through it, and the efficiency of speech transmissions is hardly affected. The magneto-generator is also bridged across the line, but its circuit is always open by the generator cut-in, except when the subscriber turns the crank (§ 406).

An assembly of the parts shown in Fig. 316 is illustrated in the perspective view in Fig. 318; the sketch needs no further explanation. The ground connection shown is used in selective signaling on party lines (§ 422).

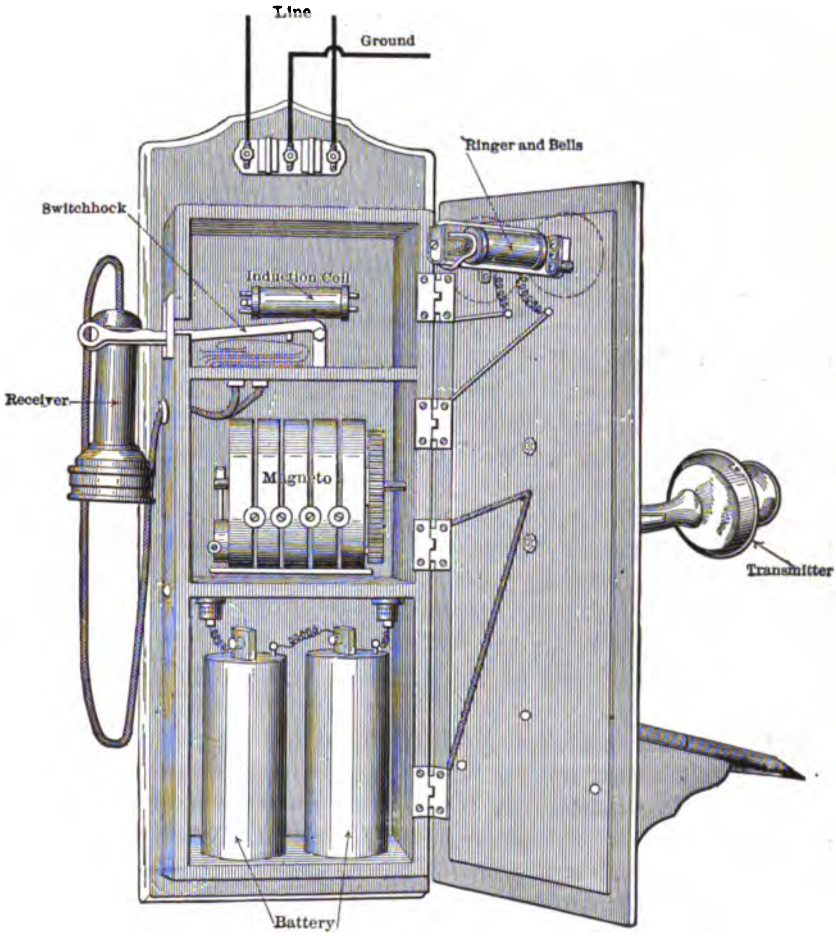

FIG. 318. Magneto-telephone set.

408. EXPERIMENT 20-B. — Connecting Magneto-Telephones. — The student is given the separate parts shown in Fig. 318, and he is expected to connect them up as in Fig. 316, possibly with slight changes, and to obtain satisfactory signaling and talking.

409. House Telephones with Battery Call. — In small house installations the magnetos and the polarized bells may be omitted, and ordinary electric bells, operated from the same batteries which supply

current to the transmitters may be substituted. The student can easily plan the necessary connections, on the basis of Fig. 316, by omitting the magneto and the induction coil.

Three conditions must be fulfilled. (1) When the receiver is on the hook, the talking circuit is open, and the bell is connected to the line, so that the subscriber may be called up. (2) When the subscriber presses the push-button, leaving the receiver on the hook, his battery is connected to the line, in order to ring the bell of the other station; at the same time his bell must not be in the circuit. (3) When the receiver is taken off the hook, the transmitter, the battery, and the receiver must be connected in series across the line. To give a hint as to the proper connections, it may be mentioned here that the battery, the transmitter and the receiver are permanently connected in series, the circuit being open at the upper contact of the switch-hook. The lower contact of the switch-hook is connected to the bell. The push-button normally closes the bell circuit, but, when pressed down, it opens the bell circuit, and closes the battery across the line. The switch-hook itself is connected directly to the line. With these instructions the student will have no difficulty in designing the proper connections.

410. EXPERIMENT 20-C. — Connecting House-Telephones Provided with Battery Call. — The student is given the telephone parts necessary for two stations, and he is expected to connect them up and to obtain satisfactory talking and ringing. It is recommended that he design the connections before coming to the laboratory, on the basis of the explanations given in the preceding article.

411. Intercommunicating Telephones. — In some cases, several telephones, installed in a building, are used for intercommunication without being connected to the city telephone system. When the number of such private telephones is not greater than 20, it may be preferable to run 20 wires through all the subscriber-sets so that each subscriber may connect his telephone with any of the remaining nineteen subscribers, without a central switchboard and an operator. A plan of connections is shown in Fig. 319: ordinary magneto telephones are used, or battery-bell telephones, and a switch is provided by means of which each subscriber can connect his telephone, to the desired subscriber, and call him up. Instead of using two wires for each subscriber, only one wire is used, the connection being completed through a common return wire, for all subscribers. Thus, with n subscribers, the total number of wires needed is $(n + 1.)$ Plugs and jacks are sometimes used, instead of button contacts and levers.

It will be noticed that the numbering of subscribers is different on different sets: The contacts on set No. 1 are: 1, 2, 3, 4; those on the set No. 2 are: 2, 1, 3, 4; etc. This is done in order to make the "home" position the first on the dial; this makes it easier for the subscriber to return the lever to its proper position after he is through talking. Unless he does so, his telephone is disconnected from his line-wire, so that he cannot be called up by any other subscriber.

This necessity for the subscriber to remember that he must return the lever to the home position, is one of the troubles encountered in the operation of intercommunicating systems: it is only natural to hang up the receiver and to forget to return the lever to the proper position. This drawback is obviated by mechanically connecting the selective lever with the switch-hook, so that hanging up the receiver automati-

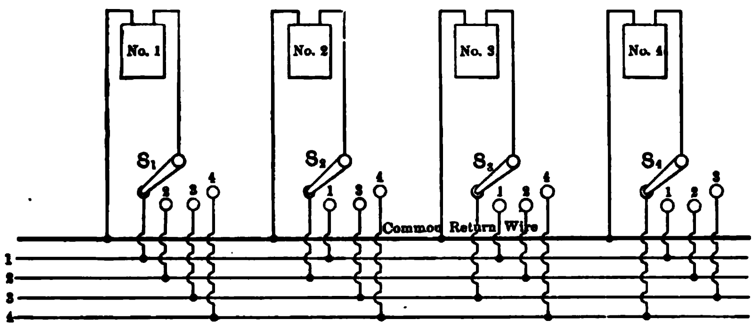

FIG. 319. Principle of intercommunicating telephone systems.

cally returns the lever to its home position. In one of the best systems of this kind, invented by Mr. Ness, the selective lever is under the influence of a spring: when the subscriber hangs up his receiver, the spring is released, and the lever snaps back to its home position. In addition to this automatic feature, the Ness system has some other noteworthy details, which are described in the next article.

412. The Ness Intercommunicating System.—The electrical connections are shown in Fig. 320: A local battery is used for talking with each set, while one common battery is provided for ringing. The reason for this is that when the telephones are scattered over a considerable distance, more cells are required for ringing than for operating the transmitters. With n subscribers the total number of wires is $(n + 2)$, there being one common talking wire and an extra call wire.

In the position, shown in Fig. 320, subscriber No. 1, having originated the call, is supposed to be in conversation with subscriber No. 2. To call up subscriber No. 2, subscriber No. 1 moves the selective switch L

to the position 2, and presses the button on the end of the switch. By doing so he sends a current from the common calling battery through the call wire and the line wire 2, into the bell of subscriber No. 2, provided that the receiver of subscriber No. 2 is on the hook. Then, after both receivers have been taken off the hook, the bell circuits are opened at the contacts *c*, shown under the switch-hooks, and the talking circuits are closed through the contacts *a*, *b*, above them. The speech transmission takes place through the wire 2 and the common talking wire. When the receiver is hung up, the spring returns the selective

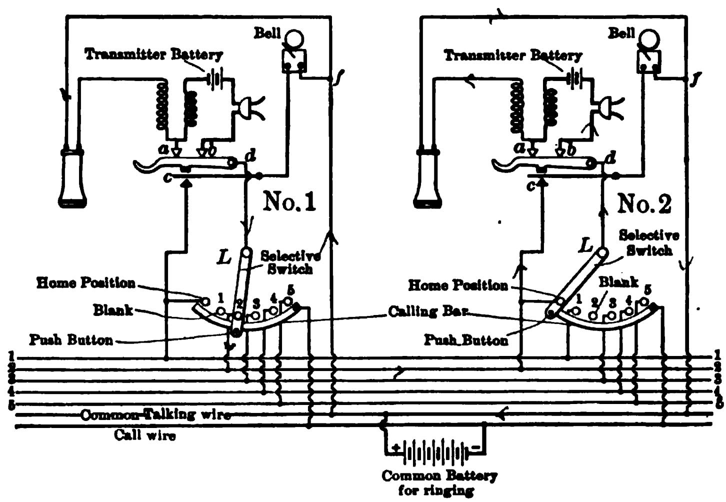

FIG. 320. Connections in Ness intercommunicating telephones.

switch *L* to its home position, and the switch-hook opens the talking circuit; at the same time the bell is connected to the line, making the set ready for the next call.

It will be noted that the contacts of all the subscribers in this system are marked in the same order, and not as shown in Fig. 319. This is made possible by providing a separate "home" contact and leaving blank the contact corresponding to the number of the subscriber. For instance, on set No. 1 the contact 1 is left blank, on set No. 2 the contact 2 is left blank, etc. The advantage of this arrangement is that all the sets are interchangeable, and all are connected to the lines in the same way. Such an arrangement can be used with any intercommunicating system, whether automatic or not.

It is not absolutely necessary with intercommunicating telephones to have the battery call: The magneto call may be used if desired, leav-

ing local batteries for talking. In some cases, one common battery is used for both ringing and talking. The only characteristic feature of intercommunicating telephones is that the subscriber is enabled to make the connections himself, without calling up the operator.

413. EXPERIMENT 20-D. — Connecting Intercommunicating Telephone Sets. — Connect up a few intercommunicating sets, following the general principles outlined above; explicit directions and blueprints of connections usually accompany the apparatus. If the set is intended for separate transmitter batteries at each subscriber, change the connections so as to use one common battery. Also, see if the connections could be changed so as to use the magneto call, instead of the battery call. Notice what occurs when a subscriber forgets to hang up his receiver; also when two subscribers try to call up the same subscriber, or when a third subscriber attempts to call up one of the subscribers engaged in conversation.

414. Magneto-Telephone Exchange. —The function of a telephone exchange, or the "central," as it is commonly called, is to suitably connect the subscribers, whose lines terminate on the switchboard of the exchange. The two wires coming from each subscriber terminate in a contact device, called the "jack" (Fig. 321). A "drop," shown in same figure, and placed above the jack, bears the subscriber's number. The drop consists of an electromagnet, and a shutter which is held in its position by a soft-iron armature. By following the connections it will be seen that when the subscriber sends alternating currents through the line, by turning the crank of his magneto, the electromagnet of the drop attracts its armature; this releases the shutter, calling the operator's attention that a connection is desired. She inserts a plug (shown to the left) into the jack and connects her telephone to the subscriber's line, uttering the familiar "Number, please." Having received the desired information, she inserts another plug, connected to the same cord-circuit with the first plug, into the jack of the subscriber to be called up; then she rings his bell by pressing a handle which connects his line to the exchange generator. At the end of the conversation the subscribers are supposed to give one or two short rings, as a signal that they are through. These signals operate in the exchange the so-called "clearing-out" drop: as soon as the shutter of this drop is released, the operator pulls out the plugs from the jacks, disconnecting the subscribers.

Following this general description of the devices used in the exchange, the separate parts will now be described in greater detail.

415. Switchboard Connections.— The jack, Fig. 321, is a double-pole contact in which a subscriber's line is terminated. The terminal

connecting to the tip of the plug is made in the form of a spring; the other contact connecting to the sleeve of the plug is made into a ring. The winding of the drop is connected on one side of the line, on the other side to an auxiliary contact, which bears on the spring contact

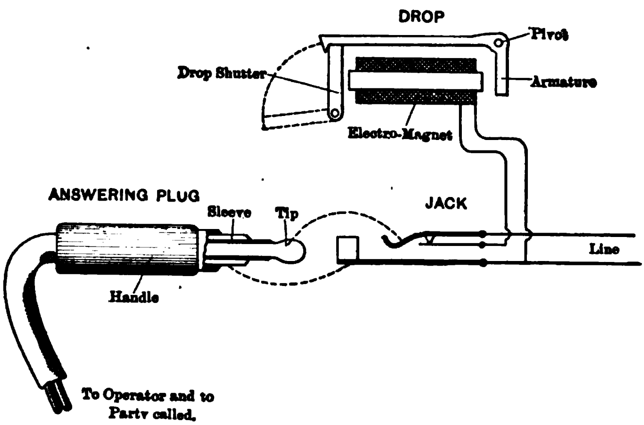

FIG. 321. Jack, drop, and plug, in a magneto switchboard.

of the jack, when the plug is not in the jack. Thus the drop circuit is normally closed, enabling the subscriber to call up the operator. When she inserts the answering plug into the jack, the tip of the plug lifts the spring and opens the drop circuit. At the same time a connection

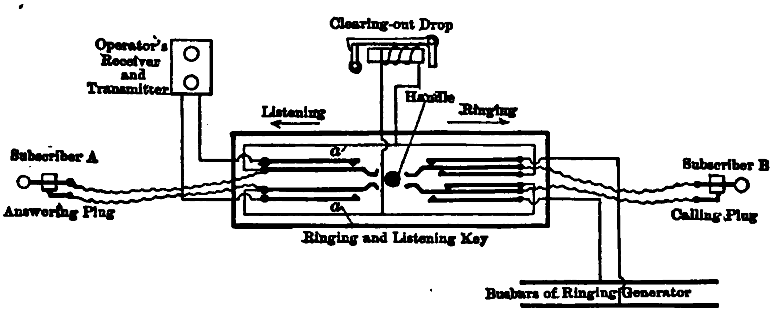

FIG. 322. Connections to ringing and listening key.

is established, through the plug and the cord, between the line and a special key called the "ringing and listening key" (Fig. 332). The left side of this key is connected to the operator's telephone set, while the right side is connected to the ringing generator and to the calling plug. When the handle of the key is in the central position, the

answering plug is connected directly to the calling plug *B*. This is the ordinary position during the conversation of two subscribers. By moving the handle to the left the operator connects her telephone to the cord circuit: this is called the "listening" position. The handle is in this position when asking the number of the party desired; also when listening for conversation, if the operator has any reason to believe that the parties forgot to "ring off."

When the handle is turned to the right, or the "ringing" position, the calling plug is disconnected from the answering plug and is connected, instead, to the generator bus-bars. This position is used for calling up a subscriber after the connection has been completed.

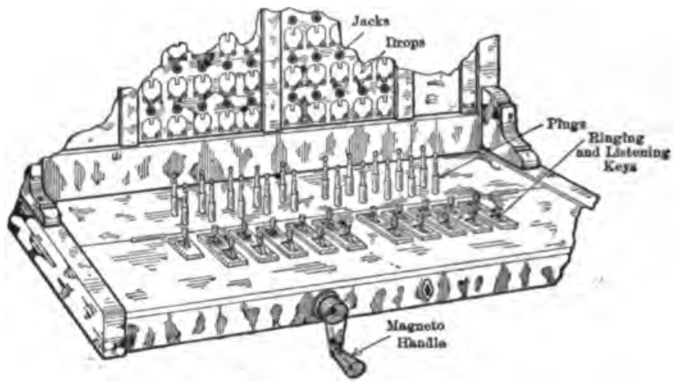

FIG. 323. Part of a magneto switchboard.

The clearing-out drop is shown on top of the sketch: it is connected directly across the cord circuit *aa* and is thus actuated by current impulses sent from either subscriber at the end of the conversation. It is not necessary to have as many pairs of plugs as there are pairs of subscribers connected to the exchange, because it never happens that all the subscribers use their telephones at once. Experience shows that ten cord-circuits are sufficient for each hundred subscribers connected to the exchange: this permits twenty per cent of the subscribers to be connected at a time. This number is never exceeded even during the busiest hours of the day.

A part of a magneto switchboard is shown in Fig. 323. The jacks and the drops are mounted on the vertical frame; the plugs and the ringing and listening keys are mounted on the horizontal shelf before it. The crank of the magneto is visible in the lower part of the cut, under the table.

416. EXPERIMENT 20-E. — Wiring a Magneto Switchboard. — An experimental switchboard should be provided in the laboratory, with drops, jacks, listening and ringing keys, etc., so arranged that the necessary connections can be easily made by the student. A few subscriber sets are to be connected to the switchboard, and the practical operation of the system studied. The explanations given in articles 401 to 415, together with Figs. 311 to 323, give all the necessary information for performing this experiment.

Report. Make sketches of actual devices used on the switchboard; give diagrams of connections if they differ from those given above. Draw in detail the connections of the operator's set.

CENTRAL-ENERGY TELEPHONE SYSTEM.

417. The above-described magneto telephones have two drawbacks:

(1) Batteries in substations require care and renewals.

(2) Turning the crank of a magneto in order to call Central is too much trouble for a busy man.

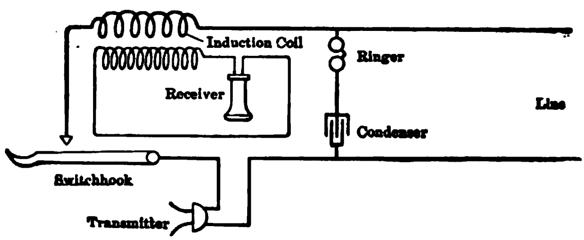

FIG. 324. Connections in a central-battery telephone set.

These inconveniences led to a gradual introduction of *common-battery* or *central-energy telephones;* practically all telephone exchanges of any importance are now equipped according to this system (see also § 405).

One of the simplest schemes of connections of a subscriber's set, in a system using a common battery, is shown in Fig. 324. When the receiver is taken off the hook, the line circuit is closed, and the battery in the exchange supplies the subscriber's transmitter with the current necessary for talking. The incoming alternating currents of high frequencies are transmitted to the receiver through the induction coil. The ringer is connected across the line and is protected by a condenser from the passage of direct currents; alternating currents for ringing pass easily through the condenser (§ 436).

Another scheme of connections is shown in Fig. 325: It differs from the previous diagram in that the receiver circuit is also opened when not in use, and is protected by a condenser against the direct current supplied to the transmitter circuit. There is little difference between the two schemes: both are simple and efficient, and both are widely used.

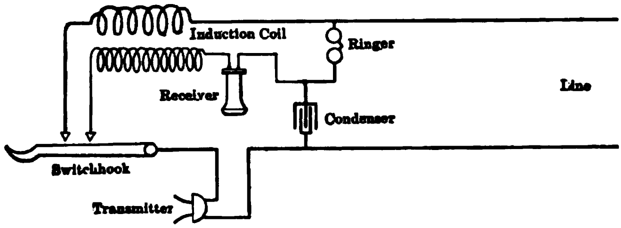

FIG. 325. Connections in a central-battery telephone set.

418. Battery Connections.— The common battery in the exchange must be connected so as to supply the subscribers with direct current for the transmitters, and at the same time offer a considerable resistance to the passage of high-frequency oscillating currents, which, if they found an easy path through the batteries, would be lost to the receiving station. The arrangements used for separating direct current from "talking" currents are based either on the action of inductance, or on that of capacity. An inductance offers an easy passage to direct-currents, but effectively prevents the passage of high-frequency oscillating currents. On the other hand, a condenser offers an infinite resistance to the passage of direct current, at the same time offering a comparatively easy path for high-frequency alternating currents.

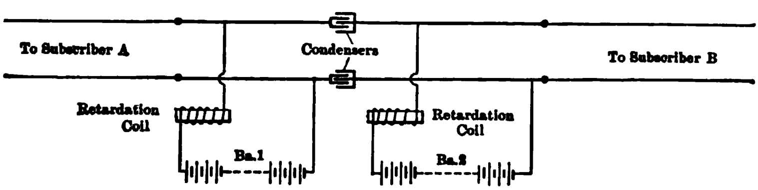

FIG. 326. Separation of talking currents from battery currents by means of condensers and retardation coils.

One application of these principles is shown in Fig. 326: Two batteries are provided in the exchange, one for the "calling" side, another for the " answering " side of the cord circuits. Condensers are interposed in the cord circuits, and the batteries are protected by so-called *retardation coils.* The latter are ordinary inductance coils, intended

to prevent talking currents from passing through the batteries. With this arrangement, direct current flows from the batteries to the corresponding transmitters, while talking currents find a direct path, from the line A to the line B, through the condensers.

With the arrangement, shown in Fig. 327, the same result is accomplished by means of a "split repeating coil." Direct current from the positive terminal of the battery flows to the point m, whence it is divided into the line A and the line B, returning to the negative pole of the battery through the point n of the split repeating coil. Oscillating currents flowing through the wires of the two subscribers magnetize the iron core of the coil in the opposite directions; therefore, the coil exerts no "choking" action between the two subscriber stations. On the contrary, oscillating currents, trying to flow through the battery, magnetize both sides of the coil in the same direction, thus creating a high-reactance path. The advantage of this arrangement is that only one battery is used, and no condensers are required.

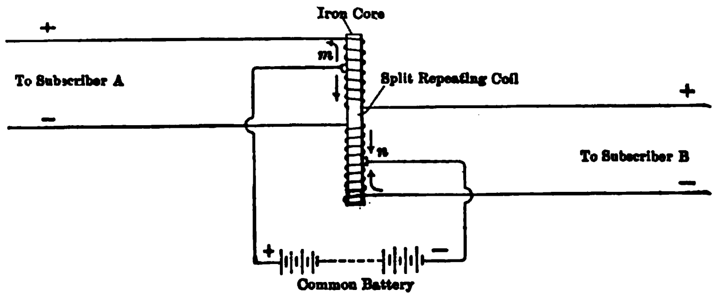

FIG. 327. Separation of talking currents from battery currents by means of a "split" repeating coil.

419. Operations Necessary for Connecting Two Subscribers. — The action of a common-battery switchboard may be understood by referring to Fig. 328. It is desired that the student should first understand the operations without following up in detail the actual wiring connections. When the subscriber A takes his receiver off the hook, the line lamp L_1, placed over his jack, lights up, calling the operator's attention to the fact that a connection is desired. She inserts one of her answering plugs into the jack A, presses the listening key k to the left, and calls for the number desired. The number being given, she inserts the calling plug of the same cord circuit into the jack of the subscriber B to be called, and presses the key to the right, thereby ringing the bell of subscriber B.

As soon as the calling plug has been inserted into the jack B, the supervisory lamp l_2 lights up, and remains lighted until the subscriber

B takes his receiver off the hook. Now the two subscribers are conversing, and all the switchboard lamps, belonging to these subscribers, are extinguished; the connection is indicated by the inserted plugs.

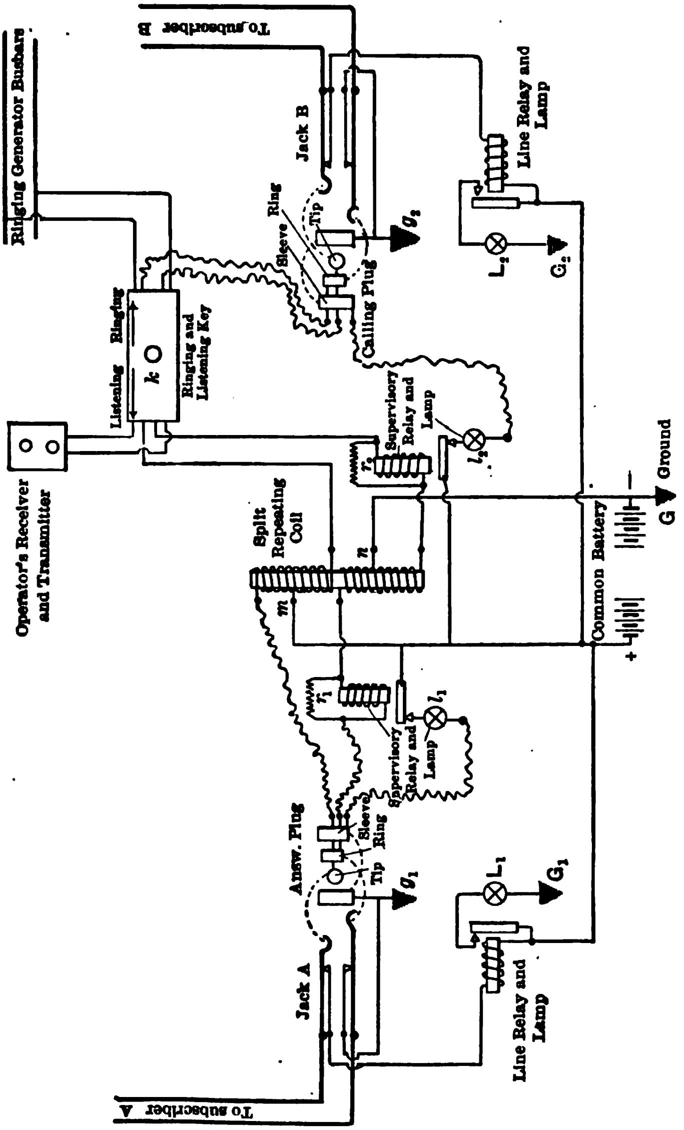

FIG. 328. Connections between two subscribers, in a central-energy exchange.

As soon as one of the subscribers hangs up his receiver the corresponding supervisory lamp lights up; when both supervisory lamps l_1 and l_2 are lighted up, the operator knows that both receivers have

been hung up. She pulls out the plugs and thereby disconnects the subscribers. If for any reason it is necessary for her to listen for the conversation, she may do so by pressing her listening key k to the left.

420. Common Battery Switchboard Connections. — Having understood the operation of the switchboard shown in Fig. 328, the electrical connections may be followed more in detail. When subscriber A takes his receiver off the hook (Fig. 324), the current from the positive pole of the common battery flows through the line relay under the jack A, through the line, and through his apparatus back to the station, and to the ground g_1. The circuit is thus completed, since the negative pole of the battery is permanently grounded. The relay attracts its armature and closes the circuit of the line lamp L_1, whereupon the lamp lights up through the ground connection G_1. Inserting the answering plug into the jack A, opens the relay circuit through the auxiliary springs, shown inside of the main contacts, and thus extinguishes the lamp.

The plugs used with this system have three contacts, instead of two, as shown in Fig. 321. These three contacts are referred to as tip, ring, and sleeve. Through the tip and the ring the talking circuit is completed, while the sleeve contact merely connects the supervisory lamp l_1 into the circuit. The battery connections for talking are the same as shown in Fig. 327. The connections to the listening and ringing key are similar to those shown in Fig. 322, and need not be repeated here.

The supervisory lamp l_1 lights up between the positive pole of the battery and the ground g_1; its circuit is opened by the armature of the supervisory relay shown above the lamp; it is also opened when the answering plug is not in the jack A. The purpose of this lamp is to indicate to the operator that the subscriber's receiver is on the hook; in other words, that he is not using his telephone. The supervisory relay is inserted in the main talking circuit and holds the lamp circuit open as long as direct current is flowing through the line A; in other words, as long as the receiver is off the hook. When the lamp lights up it is extinguished again by pulling the answering plug out of the jack, thereby breaking the connection to the ground, through the sleeve contact.

The operator's set in the above-described switchboard consists of a receiver, a transmitter, and an induction coil. The receiver and the secondary of the induction coil are connected in series, and connected to the listening key through a condenser, also in series. This condenser protects the operator from getting an undue click in her receiver when she throws the listening key in. The operator's transmitter and

the primary of the induction coil, in series with it, are all the time connected across the main battery, through a suitable resistance. The transmitter and the induction coil are bridged by a condenser, in order to offer an easier path for oscillating currents.

421. EXPERIMENT 20-F. — Wiring a Small Common-Battery Switchboard. — The student is given the necessary jacks, lamps, relays, cord circuits, etc.; also a few subscriber sets, and an operator's telephone. The experiment consists in connecting up and operating the switchboard as described in previous articles. Having obtained a satisfactory working of the system, try to determine the amount of time necessary for making a connection, from the moment when the first subscriber takes his receiver off the hook to the moment when the second subscriber answers the call.

Report. Give rough sketches of the devices used, and the exact scheme of connections employed during the experiment, at least where they differ from Fig. 328. Give a diagram of connections of the operator's set. Mention the adjustments of relays, etc., if any.

422. Party Lines. — In many cases it is desirable for economic reasons to have more than one subscriber connected to the same line. Such lines are called *party lines;* their use involves some additional problems in regard to signaling. All party-line systems used can be divided into non-selective and selective. With a non-selective system the ringing current operates the bells of all the subscribers connected to the same line, a code being necessary to distinguish between the subscribers (number of rings, short and long rings, etc.). In selective systems, only the bell of the subscriber wanted rings, leaving the other subscribers on the same line entirely unaware of the call.

In the most common of the selective systems, two subscriber sets are connected in parallel across the line, but the ringer of one of the sets is connected between the positive line and the ground, while the other ringer is connected between the negative line and the ground. The ringing generator in the exchange may be connected at will, either between the positive line and the ground, or between the negative line and the ground; thus only one bell can ring at a time. The ground takes no part in the talking circuit, the main current flowing as usual between the positive and the negative lines. Therefore, when one of the subscribers is talking, the other party connected to the same line can listen to the conversation. There is, however, very little likelihood of this, since he does not hear the call, and is not aware of the conversation on his line. The technical expression for this is: "talking metallic, ringing through the ground."

On four-party lines, *biased* ringers are used, which respond to either positive or negative current-impulses only. Of the four subscribers, bridged across the same line, two have their ringers connected between the positive line and the ground, one ringer being biased for positive impulses, the other for negative impulses. The other two ringers are connected between the negative line and the ground, and are biased for opposite impulses. The generator in the exchange is provided with a two-part commutator so as to give uni-directional impulses. In this way four combinations for ringing are made possible, and either of the four subscribers may be called up, without disturbing the other three.

The four subscribers connected to the same line are usually marked in the telephone directory with the same number, with a distinguishing letter. As, for instance:

Subscriber 127-*a* has the ringer on the right wire, positively biased.
Subscriber 127-*b* has the ringer on the right wire, negatively biased.
Subscriber 127-*x* has the ringer on the left wire, positively biased.
Subscriber 127-*y* has the ringer on the left wire, negatively biased.

A biased ringer has the same construction as that shown in Fig. 315, but is provided with a spring, which normally holds the armature against one of the pole-pieces. Thus, it cannot respond to the current impulses which would tend to bring it closer to this pole, while it responds to the opposite impulses, by overcoming the tension of the spring.

423. EXPERIMENT 20-G. — Wiring a Party-Line Switchboard. — Wire up and operate a switchboard arranged for two-party lines, and for four-party lines, with selective signaling, as explained in the previous article. Note that condensers cannot be used in series with the bell, as in Figs. 324 and 325, when the ringers are biased. This is because a condenser transforms a uni-directional current into alternating current. This brings in the difficulty that the line circuit is closed all the time, a current flowing through the bells and the ground. To prevent this current from operating the line relays (Fig. 328), the resistance of the bells is made sufficiently high, and the relays are made comparatively insensitive (marginal adjustment of relays).

424. Large Telephone Systems. — When there are more lines in an exchange than one operator can handle, more switchboard sections and more operators are added. As far as answering a call is concerned, the operations are the same as in the case of the simple switchboard, described before. Each operator is assigned a certain number of subscribers whose calls she answers. A new problem arises when the subscriber wanted has his jack on another section of the switchboard,

outside the reach of the operator. This is taken care of by providing, within the reach of each operator, so-called "multiple" jacks of all the subscribers connected to the exchange. Thus, instead of using a long cord circuit for the answering plug and inserting it into the principal jack, the operator uses a multiple jack of the same subscriber, which she finds either on her own section of the switchboard, or on one of the adjacent sections.

The use of several jacks in multiple, belonging to the same subscriber, brings in a new feature, namely, the so-called "busy" test. Without multiple jacks the operator can see at once if the subscriber wanted is already connected with some other party; but with multiple jacks she may not know that one of the jacks belonging to this subscriber has been "plugged in" by another operator, perhaps at the other end of the room. The switchboard connections are therefore so arranged, that when she touches the nearest part of the jack with the tip of the plug, she hears a click in her receiver, if the line wanted is "busy." This is because a telephone line in use is "alive": hence, making a new connection brings in a change in current and produces the above click.

With very large telephone systems the multiple connections become so complicated that it is more advantageous to use two or more separate exchanges, interconnected by a number of "trunk lines." The number of the trunk lines must be sufficient to handle the traffic during the busiest hours of the day. Dividing one exchange into several smaller exchanges has also the advantage that the subscribers' lines become shorter. When a connection is desired between two subscribers connected to the same exchange, the operations are the same as with the above-described multiple switchboard. If the subscriber wanted is connected to another exchange, the operator merely receives the call and transmits it to a special operator in the other office, who completes the connection.

Private-branch exchanges constitute a special case of the above scheme. The operator of the private branch completes the connection between subscribers connected to the branch. When, however, a connection is desired outside of the branch, she transmits the call to an operator of the main exchange, who in turn completes the connection, or, if necessary, transmits it again to another exchange.

The next development of telephone work is the long-distance transmission between cities. This traffic is handled by special operators, so-called "toll" or long-distance operators, who make the necessary connections. General features of connections may be understood from the above description of small exchanges. Special details and the corresponding laboratory experiments are outside of the

scope of this work, which does not claim to give any but general information about telephone practice. Those specially interested in telephony are referred to comprehensive treatises by Kempster B. Miller, A. V. Abbott, and others.

425. EXPERIMENT 20-H. — Influence of Resistance, Inductance and Capacity of the Line on Speech Transmission. — Connect up two telephones, to operate satisfactorily as regards talking and signaling; gradually increase the resistance of the line, until the words cannot be distinctly heard. Note a few values of resistance in the line, and mark the corresponding quality of speech as: excellent, good, fairly distinct, hardly intelligible, poor, etc. Repeat the same experiment with inductance in the line, instead of the resistance; also with a combination of resistance and inductance in series.

If large condensers are available, they may be connected across the line, either in one place or in various places, in combination with the resistance in the line itself. This will show the effect of distributed and concentrated capacity, which sometimes impairs the quality of speech, particularly with long telephone cables. Having appreciably affected the transmission by means of capacity, connect up some inductance in series with the line so as to counter-balance the effect of capacity by producing electric resonance (§ 440). The use of inductance for counteracting the capacity effect in telephone lines has been proposed by Prof. Pupin; telephone lines provided with distributed inductance coils are now known as "loaded" lines.

Appreciable disturbances in telephone lines are caused by light and power transmission lines paralleling them. Magnetic fields, produced by heavy alternating currents, induce secondary currents in the telephone lines; this impairs the quality of the speech and sometimes makes talking practically impossible. String a power line in the laboratory, parallel with the telephone line, and observe the disturbances produced. First use alternating currents and vary their strength, frequency, the distance between the wires, and the mutual arrangement of the telephone and the power lines; observe in each case the effect on the transmission of speech. Investigate the effect of *transposition* of the telephone wires, and of the power wires, so as to compensate for the effect of induction. Try this in particular with a three-phase line. Then use direct current in the power line, suddenly vary its value, and observe clicks and sounds produced in the telephones. Finally use one wire as a common return (ground) for the telephone currents and the power currents; observe the effect produced on the quality of speech.

The above combinations are those met with in practice, and are intended to illustrate the difficulties with which telephone engineers have to contend in the operation of their lines.

Report the connections used in the experiment, the values of power current, the distance between the wires, with other factors, and the extent to which they were found to affect telephone transmission. State the effect of resistance, inductance, and capacity, and of their combinations.

END OF VOL. I.

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To Vols. I and II